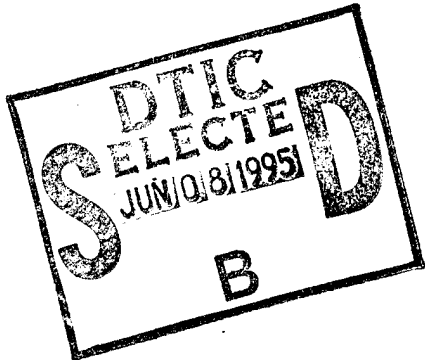


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THE EFFECTS OF DISPLAY LOCATION AND DIMENSIONALITY
ON TAXIWAY NAVIGATION

BY

JAMES WRAY LASSWELL

B.S., Colorado State University, 1987

THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Science in Psychology
in the Graduate College of the
University of Illinois at Urbana-Champaign, 1995

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THE EFFECTS OF DISPLAY LOCATION AND DIMENSIONALITY ON TAXIWAY NAVIGATION

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University of Illinois at Urbana-Champaign, 1995
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This study investigated whether taxiway navigation is best supported by head-up or head-down presentation of either perspective (3-D conformal) or plan-view (2-D non-conformal) route guidance information. Thirty-two pilots taxied in low visibility conditions (300' RVR) in a high-fidelity simulator. Pilots were instructed to maximize speed while maintaining safe control of the aircraft as they taxied along a specified route. Pilots were randomly assigned to either the 2D or 3D display condition. Each subject completed half of the trials with the display in the head-up position, and half with the display in the head-down position. Expected events were presented in both near and far domains, while an unexpected event was presented in the far domain. Results revealed that, while pilots in both groups followed the cleared route with equal success, greater mean taxi speeds were supported by the 2D display, but lateral tracking error showed a slight advantage for the 3D display. A significant number of pilots using the 2D display failed to detect and respond to the unexpected far domain event (ground traffic), resulting in six collisions. The practical and theoretical implications of these results are discussed.

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To my Lord, Jesus Christ, who provides the opportunities.

To my wife, Katie, who helps me make the most of them.

To my kids, Marcus, Adam, & Meghan, who make it all worthwhile.

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1.0 Introduction

Major automation projects are currently underway in the United States to increase the efficiency and safety of airborne traffic. Efforts coordinated by the National Aeronautics and Space Administration (NASA) and Federal Aviation Administration (FAA) promise to improve traffic flow to and from major airports by reducing separation between aircraft, improving coordination between Air Traffic Control (ATC) and pilots, and optimizing routing of airborne traffic (NASA Terminal Area Productivity Program Briefing Outline, 1993). Improvements have already been realized in supporting low-visibility landings (e.g. Alaska Airlines' Head-up Guidance System) with zero-visibility landings anticipated as the technology is fine-tuned.

However, these gains will be lost without similar improvements in ground traffic flow and safety. A pilot who successfully completes a mission and lands in zero-visibility conditions will be faced with the daunting task of rolling off the runway and maneuvering to the terminal or pad with little or no visual cues. Pilots are already familiar with the delays and confusion associated with congested and inefficient airports. Recent mishaps involving runway incursions and ground traffic collisions further highlight the need for improved ground traffic management. Efforts are needed, and currently underway, to alleviate this dangerous bottleneck. NASA's Terminal Area Productivity (TAP) Program is an attempt to increase the efficiency and safety of ground traffic. Within this program, the goal of the low-visibility taxi operations group is to develop, test, and validate a display interface to provide information for obstacle avoidance, blunder detection, and receiving/executing ATC guidance during landing, roll-out, and taxi (NASA TAP Briefing Outline, 1993). Reduced runway occupancy time, improved situation awareness, efficient taxi performance, and fewer runway incursions and accidents

are put forward as tangible benefits reaped by providing improved electronic route guidance. Several technologies are being investigated--Forward Looking InfraRed (FLIR) sensors and/or MilliMeter Wave (MMW) radar coupled with Head-Up Displays (HUD), detailed terrain/feature/airport databases linked with Differential Global Positioning System (DGPS), and ground/aircraft data-links (Batson, Harris, & Hunt, 1994; Foyle, Ahumada, Larimer, & Sweet, 1992).

Regardless of the technology to be used in supporting the pilot and crew, a central issue revolves around the interface between this technology and its user. The display must enhance a pilot's situation awareness, while minimally interfering with the taxiing task. The displayed information should be timely, relevant to the current task, easily discerned and understood, match the pilot's expectations and experience, and ultimately not distract the pilot nor compete excessively for limited resources (Ashby & Parkes, 1993)--a formidable challenge, but one that must be met or hazardous circumstances may result. The objective of this study is to examine whether taxiway navigation is best supported by head-up or head-down presentation of either perspective (3-D conformal) or plan-view (2-D non-conformal) route guidance information.

Successful navigation can be considered to involve two components: local guidance, which includes maneuvering the aircraft along a specified route (while optimizing speed and accuracy in this setting); and global awareness, which includes detection and awareness of hazards, as well as knowledge of one's own position relative to the desired destination. Thus, this study will test whether the location and dimensionality of the visual display affect these components.

1.1 The Taxiing Task

Before discussing the findings relevant to the display design issues raised in this study, it is necessary to establish what tasks confront the pilot while taxiing an

aircraft, as well as elaborating what resources are utilized. In many respects, the tasks (and information processing demands) are analogous to those required in operating a heavy car or truck (albeit in our case with the operator sitting from 5 to 50 feet above the pavement and well forward of the vehicle's pivot point). At first glance, it may appear that since the pilot is "feet on the ground" the complexity of operating the aircraft is minimal. However, as Wierwille (1993) notes, the driving task is a complex one. Wierwille's discussion provides a useful framework for analyzing the taxiing task. As in driving, the pilot must perform lateral loop closure (e.g. minimize lateral deviations from taxiway centerline), directional loop closure (negotiate turns, etc.), and longitudinal loop closure (e.g. maintain optimal speed, brake for hold markings and other traffic, etc.); information gathering inside and outside the aircraft (e.g. monitor cockpit instruments and displays, read taxiway signs and markings); and hazard detection (e.g. monitor for ground traffic, obstacles).

Nested in the definition of navigation introduced earlier, the loop closure elements can be considered part of local guidance. Hazard detection and information gathering primarily support local guidance, but overlap with aspects of global awareness. Global awareness equates to maintaining awareness of one's position relative to potential hazards, as well as to a particular destination. It should be noted that, while taxiing, the pilot falls under the authority of ground control. The pilot must adhere to the cleared route which will lead to the desired destination. The location of fixed global features (e.g. active runway, terminal, etc.) becomes less urgent than the location of ground traffic or other hazards. Therefore, global awareness involves the pilot's understanding of the dynamic changes in the world around him/her.

Within this collection of tasks, maintaining control of the aircraft (e.g. lateral, directional, and longitudinal loop closure) while vigilant to potential hazards

must be considered the primary task. This situation is the same as when flying the aircraft, where "aviate, navigate, communicate" describes the urgency of the pilot's tasks. In fact, taxiing can impose even higher demands on aircraft control due to the decreased tolerance for lateral deviations from the path while attempting to expeditiously navigate the taxiway (e.g. pilot must keep the wheels on the pavement, avoid overspeeding the undercarriage, etc.). Tasks that require the pilot to divert resources away from controlling the aircraft should be considered secondary, and only performed when safe to do so.

1.2 Resources Necessary for the Taxiing Task

In examining the resources utilized in performing the taxiing task, Wierwille (1993) again provides a good starting point. Our discussion will highlight the perceptual, attentional, and cognitive resources necessary to meet the demands of taxiing.

Perceptual Resources

As in driving, the perceptual demands of taxiing an aircraft rely on the visual system as the primary information source. It has been estimated that about 90% of all information used in driving is received through visual input (Rockwell, 1972). This input is collected through two subsystems--foveal vision and peripheral vision. Foveal vision, while limited to a two-degree field, allows the pilot to gather detailed information because of its high resolution capabilities. However, this high resolution comes at a cost. Accommodative changes are necessary whenever the eyes switch between the near and far domains. The time to refocus can be substantial (Weintraub and Ensing, 1992). Another obvious but important feature of this subsystem is the inability of humans to simultaneously extract detailed information from different positions--e.g. scan for ground traffic while monitoring a

head-down instrument. These limitations create profound implications which will be discussed later within the context of specific display parameters.

The second subsystem is peripheral vision, and is important in providing flow cues. It can also be used to detect potential hazards, particularly those that are in motion relative to the operator. With respect to other perceptual resources, the pilot does use auditory and proprioceptive/tactual cues in many situations, but these channels play a minor role in supporting the primary task. Wierwille mentions that deaf drivers can perform the driving task with little difficulty. He also notes that drivers perform satisfactorily in fixed-based simulators that provide no proprioceptive cues.

Attentional Resources

It is human attention that drives the sampling and processing of the visual environment. While a detailed discussion of the different models of human attention is beyond the scope of this study, it is helpful to characterize attention as related to the visual resource. In reviewing work by Wachtel, Wickens (1992) describes attention in perception as a searchlight. The direction that the searchlight moves describes *selective* attention. Here, for example, the pilot switches attention from viewing a route guidance display to searching for traffic along the taxiway. When the pilot exclusively examines a particular instrument (e.g. ground speed indicator), s/he attempts to ignore unrelated information and is using *focused* attention. Using the searchlight metaphor, the beam of the searchlight is fixed on a particular item and the pilot is attempting to attend to only that item. *Divided* attention, on the other hand, refers to the concurrent processing of different sources of information. For example, the searchlight beam falls on the OTW scene, but also encompasses information presented on the HUD. The pilot may be able to process both sources

simultaneously. Thus, attention serves to place the visual resource onto the necessary source of information.

Attentional resources influence not only perceptual activities, but also a pilot's ability to process information at a more cognitive level. Dingus and Hulse (1993) refer to this resource using the blanket term "cognitive attention". The pilot's eyes may be fixed on a particular region, but the information may not be processed. For example, the pilot may be day dreaming, listening to ATC communications, or attempting to plan the next maneuver. Focused attention now involves allocating attention to a particular information source for further processing (e.g. monitoring the direction of a taxiing aircraft, while ignoring the overlapping HUD imagery). Divided attention, or time-sharing, involves the efficient and concurrent allocation of attentional resources to different sources of information (e.g. monitoring for the appearance of an approaching ground vehicle, while processing ground speed information displayed on the HUD).

These two varieties of cognitive attention comprise two sides of a coin. That is, features of the visual environment may facilitate one type of attention while discouraging the other. Spatial proximity, or closeness in space, is an example of one such feature discussed by Wickens (1992). His review compares the tradeoffs associated with displaying information in close proximity to other information sources. He states that lab and field studies both show that collocating objects in space (e.g. HUD symbology) allows for more successful divided attention. Spatial proximity does not ensure parallel processing, it only makes such activity easier. On the other side of the coin, focused attention may be adversely affected when information sources are collocated. Confusion can result when overlapping images are placed in an operator's FFOV. This issue is closely related to clutter. As the information content of the visual scene increases, the demands placed on focused

attention may also increase. Thus, the time to locate and then process information will increase.

The pros and cons of placing information close together in space or on a display can be understood through theories of basic visual attention (B.A. Eriksen & C.W. Eriksen, 1974; Kramer & Jacobson, 1991). Long & Wickens (1994) provide a concise review of two alternative approaches to modeling allocation of attention to different regions in space. Space-based theories model attention as a "spotlight" that supports concurrent processing of all elements to the extent that they are in close proximity to each other. That is, if the beam of the spotlight falls on a region of space, all objects in that region will be processed. Object-based theories, on the other hand, propose that concurrent processing is supported by elements and features that lie within a single object, independent of its spatial envelope. Processing between objects will instead be serial. These authors take the position that ample evidence supports some aspects of both views (Kramer & Jacobson, 1991). Again, these issues have direct consequences related to the display parameters examined in this study, and will be discussed further in their respective context.

Cognitive attention is influenced by the demands imposed by other tasks. Dingus and Hulse (1993; citing Mourant and Rockwell, 1970) emphasize that the driving task itself does not require a constant level of attentional demand, since some driving conditions require more attention than others. The same situation holds for taxiing. Different pilots will possess varying levels of familiarity with the airport surface. Visibility conditions, geographical features of the taxiway (e.g. slopes, curves, etc.), and the level of ground traffic activity will also vary. Additionally, other cockpit tasks will require attentional resources (e.g. communicate with ATC, complete checklists, etc.). Taken together, these factors create widely different demands on the pilot. When the difficulty of the taxiing task exceeds the attention capabilities of the pilot, no amount of expended effort will keep performance

constant. In fact, performance may begin to decline. It is this increased difficulty that spurred current efforts to support pilots in the taxiing task (e.g. NASA TAP program). However, it is important to keep the attention required of the pilot below this point of performance decline. It then follows that displays need to be designed to reduce pilot workload to ensure safe and efficient performance. Once again, this philosophy becomes crucial for the foundations of this study, and will directly influence the design of the experimental displays.

Cognitive Resources

Taxiing an aircraft along the taxiway involves spatial cognition. Aretz (1991) uses the term "navigational awareness" to describe the cognitive component of keeping a vehicle on course. Navigational awareness corresponds to a pilot's knowledge of the aircraft's current location and heading relative to the desired course. To follow his route, the pilot must make a series of decisions based on the currently available information (e.g. prior knowledge, maps, FFOV, etc.). The pilot compares incoming cues to a representation of the route (e.g. map or route guidance display). This comparison involves two reference frames (RFs). The ego-centered reference frame (ERF) represents the viewpoint of the navigator, and is a function of the location and orientation of that person in space. The world-centered reference frame (WRF) is a global perspective of a given space which remains essentially unchanged as the navigator moves through it. Unless direct guidance is given within an ERF framework, the pilot must relate these two RFs through a series of cognitive operations to successfully navigate along the taxiway.

Aretz (1991) identifies four transformations which may occur: *triangulation* establishes the relative geometries of the ERF and WRF; *mental rotation* aligns the WRF and the ERF when the two are incongruent (e.g. map oriented north-up,

aircraft moving southward); *image comparison* confirms that the two RFs are aligned; and *translation* serves to monitor the ERF's movement through the WRF.

Obviously, the necessity of performing such operations depends on the physical make-up of the map or display being used to support navigation. As Wickens & Prevett (1995) point out, transformations impose costs to response time, error likelihood, and mental workload. The costs of mental rotation (both for 2-D and 3-D forms) have been well documented. Wickens, Schreiber, & Renner (1994) report that there is also a demonstrated cost associated with "navigational checking"--a term synonymous to image comparison. Given this theoretical framework, and its associated costs, an obvious consideration in display design is the need to minimize the cognitive effort required of the pilot while navigating the airport surface. This issue will be addressed when discussing the effects of display egocentricity on taxiing performance.

1.3 Sources of Input

Reviewing the taxiing task and the resources this task demands raises the question, "what information sources provide input to support performance?" The source depends on the task being performed. Using the framework introduced earlier, each task can be matched with its respective information source. Table 1 shows that the pilot receives most input from the Out-The-Window (OTW) scene--that is, by scanning and attending the taxiway environment. The pilot must locate and follow taxiway guidance cues (e.g. centerline, lights, signs, etc.), anticipate upcoming maneuvers and intersections, and scan outside the aircraft for hazards. Within the cockpit, the displays and instruments provide necessary visual information (e.g. ground speed, systems status) which supports the primary task. With the technology currently being developed, routing and ground traffic

<u>Task</u>	<u>Source of Visual Input</u>
<ul style="list-style-type: none"> • Local guidance (e.g. maneuver aircraft along cleared route) 	
Lateral loop closure (e.g. minimizing lateral deviations, etc.)	<i>OTW scene</i>
Directional loop closure (e.g. steer around turns, etc.)	<i>OTW scene</i>
Longitudinal loop closure (e.g. maintain optimal speed, braking, etc.)	<i>Instruments/Displays, OTW scene</i>
Hazard detection (e.g. monitoring for other ground traffic, obstacles)	<i>OTW scene, Display*</i>
Information gathering (e.g. scan taxiway signs, markings, lights; scan instruments)	<i>OTW scene</i>
<ul style="list-style-type: none"> • Global Awareness (e.g. maintain awareness of position relative to airport features, destination, etc.) 	<i>Display*</i>
Note: Primary information sources are <i>Italicized</i> .	
*Electronic display envisioned under NASA TAP Program will provide information re: A/C dynamics, ground traffic, ATC clearances, etc.	

Table 1: Information Sources for Taxiing Task .

information will be presented on a display located in the cockpit. Each of these sources impose specific constraints on the ability of the pilot to process them.

Adapting a representation put forward by Long & Wickens (1994), Figure 1 illustrates the interaction between attentional resources and the location of visual input. Taxiing the aircraft can involve 1) focusing attention exclusively on the far domain (e.g. tracking taxiway centerline to minimize lateral deviations), 2) focusing attention on instruments or displays in the near domain (e.g. reading ground speed information from either head-up or head-down display), and 3) integrating related or redundant information from both domains (e.g. in our setting, tracking a highlighted centerline presented on the head-up display that is conformal to the taxiway centerline). It is imperative that the information presented on displays supports efficient allocation of visual, attentional, and cognitive resources. This interaction again has profound ramifications which will be discussed shortly.

1.4 Display Parameters

With the psychological foundations related to the taxiing task laid, the display issues raised by this study can now be considered. As stated earlier, this study will examine whether taxiway navigation is best supported by head-up or head-down presentation of either perspective (e.g. fully ego-referenced) or plan-view route guidance information. This experimental design raises the issues of 1) display location--where should the information be placed, head-up or head-down? This factor in turn raises the issue of conformality with regards to the display symbology; 2) display perspective--should the display represent information from the viewpoint of the operator or from a more world-oriented frame of reference. Perspective in this setting refers to a myriad of related features: Should the information represent a fully egocentric perspective or some degree of exocentricity? Should the information be represented in 2-D or 3-D? Should the information move in accordance with the operator's momentary viewpoint (e.g. rotating or track-up

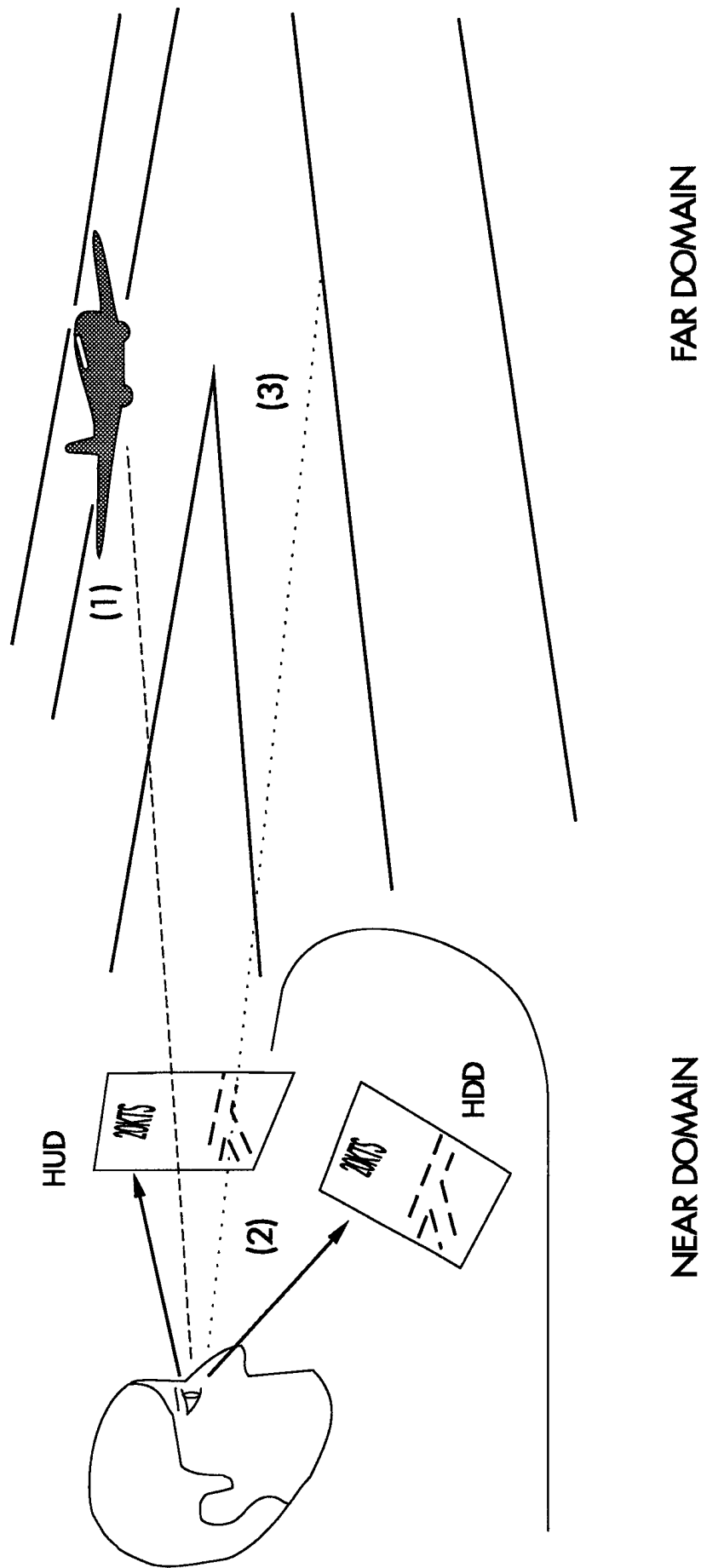


Figure 1: Symbolic representation of pilots' attentional processing between the near and far domains when using head-up and head-down symbology. Processes (1), (2), and (3) are described in the text.

display vs. fixed display)? These issues will be discussed within the framework introduced during the task analysis of taxiway navigation.

Display Location

Today's technology makes it possible to present complex information either head-up or head-down. Advances in computer-generated imagery allow virtually anything that can be presented on a CRT to be projected head-up. The limiting factor is the human operator. Several studies and reviews demonstrate that complex in-vehicle displays require more frequent and longer duration scans to process information (Antin, Dingus, Hulse, and Wierwille, 1990; Ashby and Parkes, 1993; Dingus, Antin, Hulse, and Wierwille, 1988; Obata, Daimon, and Kawashima, 1993; Popp and Farber, 1991; Schraagen, 1993; Walker, Alicandri, Sedney, and Roberts, 1990; etc.). Thus, while one of the main advantages of using CRTs to present complex information is the flexibility in displaying this information, concerns arise over the wisdom of such an approach (e.g. Zwahlen & DeBald, 1986). Complex displays require allocating additional visual and attentional resources to process information. This requirement means that the operator's eyes move off the OTW scene for longer periods of time. Careful consideration must be given to avoid overloading and/or distracting the operator.

With this limitation in mind, does one display configuration win out over the other when information content and form are held constant? Head-up displays (HUDs) are devices used in modern aircraft and automobiles to superimpose imagery (near domain) on the external outside scene (far domain). These devices were originally designed as a means of placing pertinent information into the pilot's FFOV, thus reducing the amount of scanning between the two domains. First placed in military aircraft, HUDs are seeing increased use in commercial and general aviation, as well as tentative marketing in automobiles (Harrison, 1994; Weintraub

and Ensing, 1992). At the same time, the use of CRTs is also undergoing an explosion. Conventional instrument panels are being replaced by multi-function displays (MFDs) in newer generation aircraft. Automobile instrument panels are also being redesigned to incorporate navigation and information displays. These changes are attempts to support the operators as the complexity and amount of information associated with their tasks continue to increase. The question remains, however, "which display configuration will best support the operator?"

Each configuration has advantages and drawbacks. Presenting information head-up provides the potential benefits of reducing the scanning distance between the display and the OTW scene, reducing the accommodative changes necessary to switch between domains, and allowing for conformal imagery. These advantages are pitted against the problems of clutter and "cognitive capture". Each of these issues will be discussed in order.

For the taxiing task, it can be argued that the pilot should maximize the time spent scanning the OTW scene (see Table 1). Keeping "eyes out" supports safe control of the aircraft (e.g. lateral, directional, and longitudinal loop closure), efficient information gathering, and importantly, detection of hazards. Weintraub & Ensing (1992) outline the benefits and issues associated with different display locations. HUDs offer the benefits of 1) reduced scanning, allowing both foveal and peripheral vision to remain within the envelope of the external environment, and 2) fewer changes in accommodation when switching between domains, since the optical distance of HUDs differs less from the optical distance of the outside scene compared to HDDs (See Weintraub & Ensing, 1992 for review of accommodation controversy).

An additional factor that is a potential benefit of head-up presentation is conformality. Figure 2 (adapted from Long & Wickens, 1994) illustrates how HUD symbology can be considered to lie along a continuum from fully conformal to

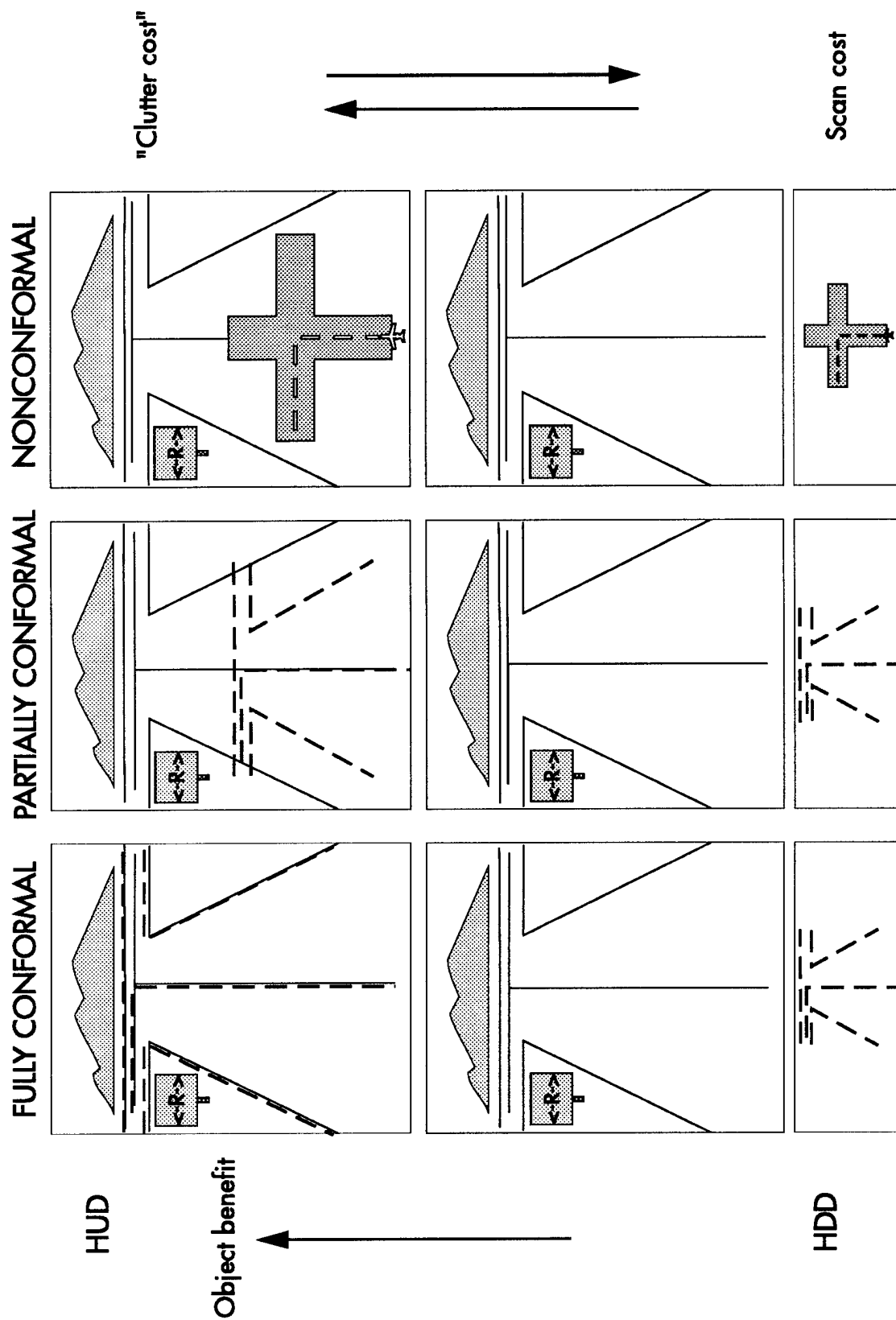


Figure 2: Head-up display (HUD) vs. head-down display (HDD) symbology illustrating the continuum of conformity. Left column: taxiway outline is fully conformal; middle column: taxiway outline is partially conformal; right column: 2D map is non-conformal.

partially conformal to non-conformal. **Fully Conformal** (FC) imagery is linked to the far domain and provides a virtual analog to its external counterpart. The image spatially overlays the environmental object, sharing common shape and motion features. Gestalt properties of "common fate" serve to fuse the two domains into one perceptual object. As noted in the discussion of attentional resources, this fusion may facilitate switching attention between the symbology and the far domain since only a single object needs attending.

Partially Conformal (PC) imagery is similar to FC symbology in that it shares similar form and moves in synchrony with its far domain counterpart. However, this imagery does not always spatially overlay its counterpart (see Figure 2). For head-up presentation of PC symbology, it can be argued that a fusion/clutter "tug of war" may result. May & Wickens (1995), in discussing work by Yantis (1992), concluded that synchronous motion allows display elements to be perceptually bound as features of the same object. This finding tends to support the idea that PC symbology "fuses" with its environmental counterpart and should enjoy the same benefits. The results from the May & Wickens (1995) study support this claim, but it should be noted that the symbology used in their manipulation did not have a visual counterpart in the far domain. Pilots using PC symbology performed equally as well as pilots supported by FC symbology.

Finally, **Non-Conformal** (NC) imagery does not spatially overlay or "conform to" any far domain feature. This symbology would potentially create a clutter cost in head-up presentation. Thus, head-up presentation of symbology may capitalize most effectively on conformal imagery.

These benefits are counterbalanced by the cost of clutter created by overlapping images. Superimposing images over the external scene may mask important far domain information, especially pertinent to the detection of hazards (Kaptein, 1994; Weintraub & Ensing, 1992). This clutter may also contribute to the

problem of cognitive capture (also referred to as attentional capture or tunneling). Placing information within an operator's FFOV may create an involuntary attraction of attention to the HUD, even when there is no need to attend to it (Martin-Emerson & Wickens, 1993; Weintraub & Ensing, 1992). This claim is supported by several studies which found that pilots using HUDs frequently failed to detect a runway incursion (Fisher, Haines, & Price, 1980; Larish & Wickens, 1991; Long & Wickens, 1994; Weintraub, Haines, & Randle, 1985). Figure 2 shows how these forces may cancel each other out depending on the circumstances. Thus, there may be no relative advantage for head-up over head-down presentation, and perhaps even a potential performance cost.

How do these factors play out in relation to head-down presentation? It is obvious that CRTs impose a scan cost--the pilots must bring their eyes into the cockpit to process the display. But is this cost significant? Wierwille, Hulse, Fischer, and Dingus (1991) found that drivers adapt reliably and appropriately to both anticipated and unanticipated increases in driving task demand while using an in-vehicle navigation system. The switching between the near and far domain also requires the eyes to refocus. Both of these costs potentially translate into a failure to detect events in one domain while fixating in the other. However, an advantage of this configuration is the absence of clutter superimposed on the OTW scene, avoiding the issue of environmental masking and attentional capture.

Numerous studies within aviation and automotive settings have examined the performance tradeoffs created by each configuration. Unfortunately, very few have carefully controlled the design to allow comparison between head-up and head-down presentation of identical information. The studies that did control for symbology offer some understanding of how display location affects performance and will now be reviewed.

- Macroperformance issues

For this discussion, macroperformance refers to tasks such as tracking vehicle position, controlling speed, and maintaining desired heading. To successfully complete these tasks, the pilot must efficiently allocate attention between the near and far domains. As illustrated by Figure 1, some tasks will require focused attention, while others can be optimized by dividing attention. By examining the effect of display location on macroperformance, insight into the dynamics of attentional control may be gained.

Aviation studies:

Weintraub and Ensing (1992) completed an extensive review of the aviation literature, carefully considering any confounding factors in each study. Parks and Tubbs (1970) had pilots observe videotaped approaches and report "...position relative to glide slope and centerline at the outer marker and middle marker, decision at DH (decision height), and estimated aim point in feet from threshold and to the right or left of centerline". The same symbology was presented head down on a CRT or on the HUD. There were no significant performance differences between the display configurations. Boucek, Pfaff, and Smith (1983) employed three displays--1) a Bray-like HUD, 2) a conventional head-down instrument panel (HDIP), and 3) the same HUD symbology presented head-down and to the right--to support pilots completing approaches all the way to landing in a Boeing 737 flight-crew training simulator. Of interest to this study, flight performance with the HUD was only slightly superior to that using the HUD symbology head-down. Based on these and other studies, Weintraub and Ensing (1992) maintain that when identical symbology is presented, flight performance is not dramatically affected by display location.

Additional studies also failed to find decisive advantages for flight performance supported by a particular display location (e.g. Larish & Wickens, 1991; Martin-Emerson & Wickens, 1993).

Recently, Long and Wickens (1994) reported that HUDs do show an advantage in tracking performance. The authors instructed pilots to fly instrument approaches in a high-fidelity visual simulator, first within instrument meteorological conditions (IMC) and then out of the clouds in visual meteorological conditions (VMC), using either conformal or non-conformal flight guidance information. Each pilot flew half of the trials head-up, the other half with the information head-down. Results indicated that conformality of the symbology differentially affected performance dependent on the visual conditions. While flying in IMC, pilots achieved superior position tracking using non-conformal symbology on the HUD over the other display variations. However, when the pilots broke out of the clouds, head-up conformal symbology supported better position tracking. Based on these results, the authors conclude that the HUD supports superior performance, and capitalizes most effectively on conformal imagery under VMC.

Finally, results from a low-fidelity simulator study by May & Wickens (1995) indicate that, contrary to the studies mentioned thus far, HDDs show an advantage for aircraft control. Pilots were instructed to follow a designated flight path using either a HDD or HUD (of varying intensities). Contrary to the authors' own expectations, vertical and lateral tracking, as well as airspeed tracking showed decreased error under the HDD condition. The authors speculate that these results could reflect the effect of poor contrast between HUD symbology and dynamically changing background and/or a result of the limitations of focused attention related to clutter introduced by superimposed symbology.

Putting these aviation studies in the context of taxiway navigation, do these conflicting results shed light on the possible effects of display location on taxiing

performance? There are obvious differences in the tasks associated with flying and maneuvering along the airport surface. The former involves controlling motion in three dimensions, while the latter is confined to two dimensions. It may be that removing one axis of control will reduce pilot workload even further, resulting in no differences in taxiing performance between display locations. However, based on the results of Long & Wickens (1994), a display utilizing conformal route guidance symbology may support superior allocation of attention. If the information presented on the route guidance display was conformal to the taxiway environment, performance may improve. Nonetheless, it is altogether not clear how well these results generalize to our present setting.

Automotive studies:

The automotive literature also contains relatively few studies comparing display location while carefully controlling confounding factors. Additionally, most studies fitting this requirement used displays which presented only speedometer information. However, these studies do provide possible insights into the performance changes associated with display location, and thus provide a good starting point for our discussion.

Kaptein (1994) instructed drivers seated in a high-fidelity fixed-base driving simulator to minimize lateral tracking error while keeping speed at a specified target. The task was complicated by unpredictably varying side and headwinds. The drivers were supported by one of three analog displays--HD speedometer, mirrored HU speedometer, projected HU speedometer. Results showed a clear advantage of HUD over HDD in lane keeping, speed control, and subjective workload. This study is significant in that it utilized a paradigm that allowed for careful control over the experimental variables while imposing realistic task demands.

In a field study, Kiefer (1991) compared visual sampling behavior and speed control performance of drivers operating a vehicle equipped with either a head-up or head-down digital speedometer. Results indicated that speedometer location had no effect on speed control performance (percent of time above 35 mph speed limit)--that is, subjects in both groups violated the speed limit with equal frequency. However, differences were observed in visual sampling behavior--drivers took less time (overall 144 msec less) to scan from the roadway to the speedometer, fixate, and then scan back out to the roadway when using the HUD. Kiefer states that driver performance did not conclusively reveal which display location is most appropriate. He also concludes that this null result may be a consequence of the relatively low task demands (e.g. ceiling effect masked performance differences).

Sojourner and Antin (1990) did note differences in performance in an investigation utilizing a simulated driving environment to examine the effects of HUD and HDD speedometers on three perceptual tasks associated with driving an automobile--speed monitoring, navigation, and salient cue detection. (This last task will be discussed under microperformance issues since it deals with monitoring for environmental hazards rather than actual vehicle control.) In this study, subjects viewed a videotaped route as seen from a driver's perspective while the digital speedometer was either superimposed on the scene (HUD) or presented on a CRT in front of the subject (HDD). For the speed monitoring task, subjects were to orally report whenever the speedometer indicated that the vehicle was exceeding the posted speed limit by at least 5 mph. The navigation task required continual monitoring of the environmental scene and orally indicating when deviations from a previously memorized route occurred. The HUD yielded better speed monitoring performance, but no significant differences in performance in the navigation task.

Taken together, these "speedometer" studies show that presenting information on a HUD can achieve appreciable benefits. However, only one

(Kaptein, 1994) approached realistic levels of environmental demand. An additional factor reducing the significance of these results relates to the display. All three studies examined performance using a simple display presenting only speed information. The demands of processing the display were potentially less than would be expected for a navigation or route guidance display. Also, the head-up speedometers were located near the bottom of the windshield, effectively avoiding most clutter costs.

Only one study was found that examined performance supported by a fairly complex visual display located in either a head-up or head-down location. Unfortunately, the paradigm utilized a stationary visual scene and failed to create realistic levels of task demand. Green and Williams (1992) presented static slides of a residential intersection photographed from a driver's viewpoint to subjects seated in a vehicle mockup. Simultaneously, a navigation display was presented head-up or head-down. The subjects indicated if the two images represented the same or different type of intersection (e.g. cross, Y, T, etc.). While there was no difference in error rates, mean response times indicated that HUDs were superior to HDDs (average response 100 msec faster). Despite its limitations, this study begins to approach the necessary levels of display complexity that can be expected in a route guidance display. The quicker response time found under the HUD condition should be scrutinized under more realistic environments as suggested by the authors.

As with the aviation studies, when put into the context of taxiing an aircraft, the automotive research fails to decisively predict the effect of display location on real-world navigation performance. As stated earlier, a major problem prevents generalization -- in the "speedometer" studies, the HUD symbology consisted of either an analog or digital speedometer located below the operators' line of sight. Thus, only one type of information needed to be attended, uncomplicated by clutter from the background scene. The scan time necessary to retrieve the information was

reduced without competing against the cost of clutter. Thus, it is really no surprise that these studies resulted in generally superior performance using the head-up speedometer.

The display envisioned for supporting taxiway navigation can potentially take on many forms. What is certain, however, is the relative complexity of the display that will be necessary to effectively support the pilot. Competing demands from other tasks (e.g. controlling aircraft dynamics, monitoring instruments, etc.) will also be significant. Additional research is needed to compare performance supported by a fairly complex display under conditions more closely representing real-world scenarios.

•Microperformance issues

In discussing the effects of display location on microperformance, reference is made to performance on tasks requiring detection and monitoring of discrete events--expected and unexpected. Performance on these tasks again requires the pilot to maintain awareness of both domains. By examining the operator's ability to detect and respond to events, both on the display and in the environment, the effect of display location on attention switching can be ascertained. This understanding can, in turn, lead to inferences regarding global awareness. Response to a discrete event is dependent on whether the subject has prior knowledge that an event will occur, or if the subject is "surprised" by an event. Thus, we will consider these two levels of expectancy separately in the following discussion.

Aviation studies--expected events:

Weintraub, Haines, & Randle (1984, 1985) presented static slides of a runway photographed from the perspective of final approach to pilots. The subjects viewed these images and made decisions regarding runway status and flight

parameter limits using either a HDD or HUD. The authors found that switching attention between domains was facilitated by the collimated HUD compared to the HDD located close-in. Wickens, Martin-Emerson & Larish (1993) replicated these findings using a high-fidelity simulator, finding that response times were quicker using the HUD for both near and far domain events.

Several authors have replicated the results of these two studies to varying degrees. Larish & Wickens (1991) using a low-fidelity simulator with the collimated displays, and Martin-Emerson & Wickens (1993) using a high-fidelity simulator, noted an advantage for the HUD in detecting near domain events (e.g. changes in display elements), but failed to find a significant difference in monitoring far domain events with either display location. May & Wickens (1995), utilizing a low-fidelity simulator with non-collimated displays noted a HUD advantage for detecting aircraft targets (far domain). These authors noted a disadvantage in monitoring for display events (near domain) in the HUD conditions, but primarily under low contrast conditions (e.g. HUD symbology set at a low intensity while presented against VMC). When contrast between HUD symbology and the OTW scene was increased, this disadvantage was significantly reduced.

Long & Wickens (1994), using a high-fidelity simulator, failed to find a significant effect of display locations on event detection in either domains. The authors note that, while not statistically significant, the mean latency in reporting "runway in sight" showed a trend towards a HUD advantage.

The general conclusion from these studies points toward a possible HUD advantage in detecting near domain events, as well as detecting far domain events when these events are expected. The cause of this advantage can be argued, but it may relate to the reduced scanning required when the symbology is placed in the pilot's FFOV.

Aviation studies--unexpected events:

Superimposing information on the external environment allows this imagery to be placed in the FFOV to reduce scanning, but it also creates clutter. Several studies have noted a degraded response time in detecting far domain events that were unexpected when using a HUD (e.g. Fischer, Haines, & Price, 1980 and Long & Wickens, 1994 employing high-fidelity simulators; Larish and Wickens, 1991 using a low-fidelity simulator with collimated displays; Weintraub, et al., 1985 using static slides). One high-fidelity simulator study failed to replicate this phenomenon (Wickens, Martin-Emerson & Larish, 1993), finding no significant difference in response times to a runway incursion between the two display locations (although the non-significant differences did favor the HDD).

Only two studies (Larish & Wickens, 1991; Wickens, Martin-Emerson & Larish, 1993) measured the effect of display location on unexpected events occurring in the near domain. Larish & Wickens found that under conditions of high workload, the HUD showed a disadvantage, while Wickens, et al. (1993) noted no difference in performance with respect to unexpected near domain events.

Automotive studies--expected events:

In an earlier discussion of the study by Sojourner & Antin (1990) it was noted that performance under both display configurations was good, but that the HUD condition produced generally superior performance on all three tasks. Of particular importance to this study, the subjects detected and responded more quickly (averaged 440 msec) to the salient cue. The cue mimicked a child's ball, and subjects were instructed to consider it a potential roadway hazard. Subjects were informed that this cue would appear at one of three locations within the scene at random intervals. Thus, while not certain of when or where the cue would appear, the subjects expected this far domain event during the trials. The authors speculate

that the quicker response resulted from the HUD subjects' gaze being directed on the environmental scene (e.g. reduced scan cost, less accommodative change required).

- Conclusions related to display location

Based on this review, it is difficult to predict if taxiing performance will be affected by display configuration. While many studies noted benefits for HUDs (e.g. Green & Williams, 1992; Kaptein, 1994; Larish & Wickens, 1991; Long & Wickens, 1994; Sojourner & Antin, 1990), these studies are difficult to generalize due to the limitations already mentioned. There is strong evidence that HUDs result in quicker detection of expected events, both on the display and in the far domain. Ability to detect far domain hazards (e.g. unexpected events) also appears to be strongly influenced by display location, with a distinct disadvantage for head-up presentation. Wickens, Martin-Emerson, & Larish (1993) speculate that when events are extremely rare (e.g. runway incursion), perception may be based completely on bottom-up processing. The salience of an unexpected event may be reduced by the presence of superimposed imagery, making detection more difficult. Again, clutter may be counteracting the benefits of reduced scanning in this situation. However, when expecting an event, top-down processing can assist in filtering out the background "noise", allowing the benefit of reduced scanning to surface.

It was expected that pilots in the present study would perform in a similar fashion--that is, they would show no significant differences in detecting expected events in both domains, but experience difficulty in detecting unexpected far domain events. These evidence from the studies reviewed suggests that HUDs should only be used for high-priority information, and possibly for information that is displayed in reference to the external scene (Kaptein, 1994 citing Assman, 1988 and Ward, Stapleton, & Parkes, 1993).

Display Perspective

Navigating the taxiway has already been defined as involving local guidance (keeping the aircraft on the desired path) and global awareness (knowing own position relative to other ground features). Wickens & Preveett (1995) provide an introduction into how these tasks play out with respect to characteristics such as display perspective. Figure 3 (adapted from their study) shows that information supporting local guidance should be presented in an ego-referenced frame (ERF). The display should faithfully represent the feedback given to the operator from the forward visual scene. As the pilot makes inputs for vehicle control, the display should match the features of the outside environment. Such a display may be characterized as "ecological" (Warren & Wertheim, 1990). That is, the information highlights and emphasizes a forward "cone" of visual space in front of the navigator, "zooming in" to represent near space more precisely than far space. The information should also represent the world in 3-D perspective. Based on their review, a local guidance display should mimic the observer's view by being: ego-referenced, forward viewing, "zoomed in", and 3-D.

Figure 3 also outlines the knowledge states necessary for global situation awareness (Endsley, 1993). These states are fundamentally different from those needed for local guidance, and are less ecological in nature. As discussed earlier, the responsibilities of the pilot change upon landing. Ground control provides precise routing which the pilot must follow. If the pilot becomes disoriented or takes a wrong turn, s/he must immediately stop and contact ground control for updated instructions. Ground control personnel are responsible for maintaining global awareness of aircraft position relative to the desired location. Thus, global awareness in the taxiing environment requires less knowledge regarding geographical features, but an accurate understanding of the position of potential hazards for rapid and accurate response. For example, the pilot must monitor the

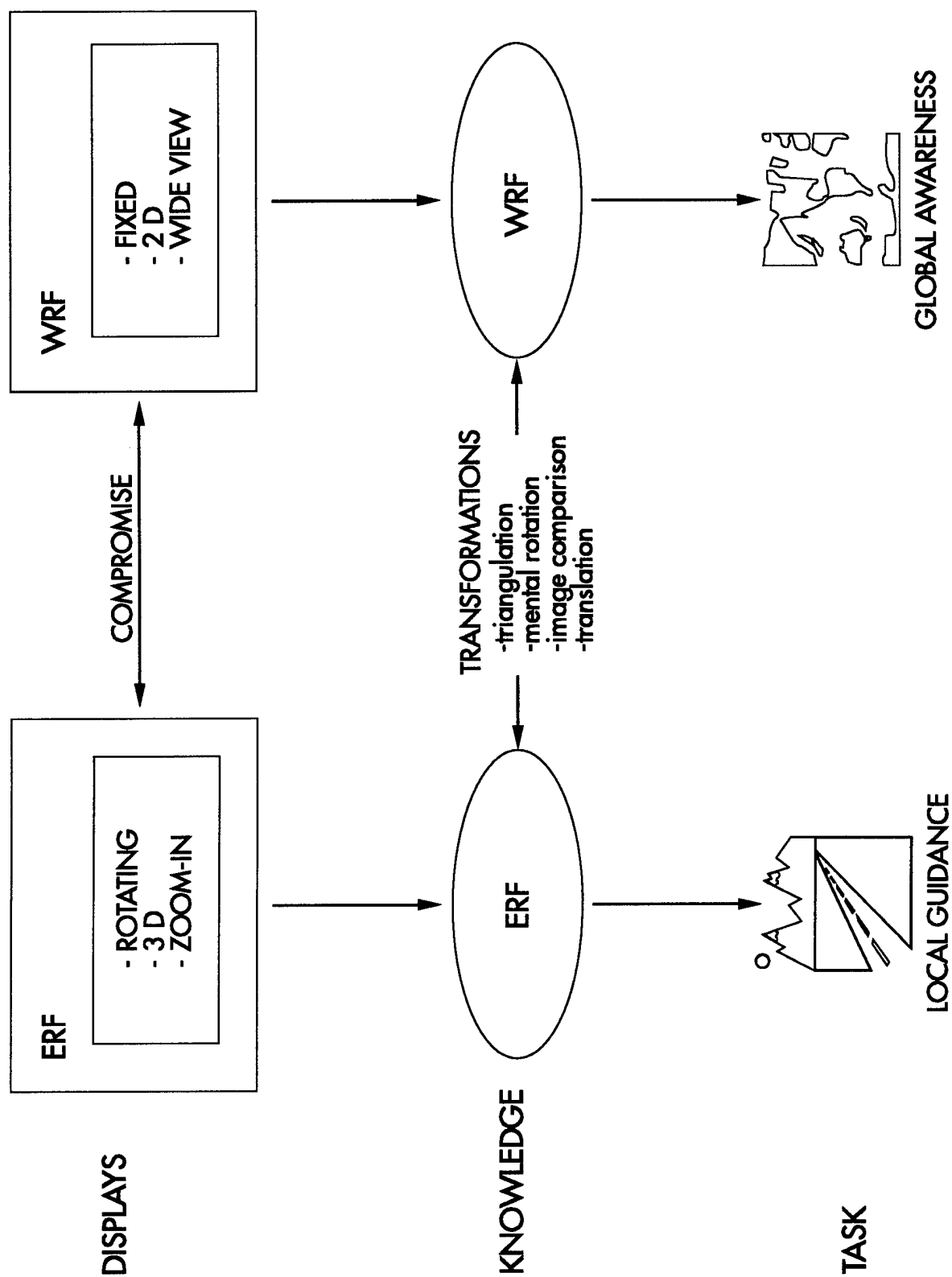


Figure 3: Representation of the continuum between ego-referenced information supporting local guidance and world-referenced information supporting global awareness.

taxiway for other ground traffic which may cross his/her path. The pilot must also maintain awareness of active runways and hold positions.

Such factors move the knowledge states necessary for global awareness, and therefore information displays supporting this task, from an ERF to a world-referenced frame (WRF). Such a RF facilitates communications with others (e.g. ATC, other ground traffic) who may not share the same momentary ERF. The display would now reflect information about the environment in fixed global coordinates (e.g. North, South, etc.). Such a frame lessens the requirement for 3-D perspective, because this perspective, by definition, assumes a particular ego-referenced position. Finally, to improve global awareness, the information should depict a broader region of the world by zooming out to a "wide angle" view allowing for greater preview of the environment.

Relating these representations to the spatial cognition required of the pilot while taxiing, it appears that the displays should be more "ecological" in nature to support efficient processing for local guidance. However, such a display would create additional processing demands for global awareness tasks to the extent that such tasks are based upon world-referenced information. As Wickens & Preveet (1995) note, these two navigation tasks are often related, making an optimum display elusive.

- Track-up vs. North-up

Aviation literature:

The findings from this body of research offer fairly robust guidelines for formatting navigation displays. Unfortunately, these guidelines are more applicable to the 3-dimensional realm associated with flying, rather than the ground-based taxiing environment. Generalizing these results to our present study should be done cautiously.

Wickens, Liang, Prevett, & Olmos (1994a) reviewed research dealing with mental rotation (e.g. Aretz, 1991; Aretz & Wickens, 1992; Baty, Wempe, & Huff, 1974) and found that rotating (track-up) maps alleviate the need to perform mental rotation often required for ERF-WRF comparisons and directional control. Therefore, such maps are generally superior for local guidance (authors citing Aretz, 1991; Rate & Wickens, 1993; Shepard & Hurwitz, 1984). Wickens, et al. (1994a) offer a second conclusion (based on Aretz, 1991) with less certainty--fixed maps allow for better learning of environmental features, and may lead to superior global awareness.

Recently, Batson, et al. (1994) confirmed that rotating maps do provide advantages for local guidance during taxiing operations. Pilots in this high-fidelity simulator study maneuvered an aircraft along a specified route supported by either a conventional paper map or an electronic 2-D map. Significantly, pilots had the option of using the electronic map in "north-up" or "heading-up" mode, and uniformly spent most of the time in the heading-up setting. Results showed that, compared to the paper map condition, average taxi speed increased with the electronic map under both visibility conditions (150 feet RVR and VMC). The authors conclude that this gain was partly due to eliminating the time used for orientation with the paper map. Pilots also achieved better centerline tracking and made fewer navigational errors when supported by the electronic map. Again, the authors suggest that this resulted partly from reduced manipulation of the paper map, and partly from increased confidence of the pilots. Most of the pilots commented that the electronic map gave them better awareness under both visibility conditions.

Together, these findings demonstrate that rotating, rather than fixed, maps provide clear and unambiguous advantages for local guidance. Although there are some potential costs associated with rotating maps in terms of reduced global awareness, these costs appear to be outweighed by the advantages for route

guidance. For example, the taxiway environment imposes severe constraints on the pilot relative to the skies (e.g. taxiway pavement fairly narrow, turns and curves must be followed precisely within specific limits to avoid aircraft damage, etc.) that raise the cost of navigational errors. If heading south while using a north-up map, the pilot could potentially confuse turns to follow the cleared route and make inappropriate control inputs. Rotating maps should avoid this confusion and prove advantageous for ground-based operations.

Automotive literature:

As efforts to develop in-vehicle navigation systems intensified, researchers attempted to apply basic principles from spatial cognition research (e.g. Thorndyke & Hayes-Roth, 1982) to display design. Commercially available navigation systems (e.g. Etak) were marketed which acknowledged this influence by giving drivers the option of selecting heading-up or north-up map displays. However, relatively little work has been accomplished that systematically compares these modes. A recurring theme in much of the automotive display literature is the need for increased research to examine such issues.

Antin, Dingus, Hulse, & Wierwille (1990) evaluated the effectiveness and efficiency of navigating with a moving-map display (track-up), a paper map, and a memorized route (used as comparison baseline) while driving a vehicle along roads in varying states of complexity. Results indicated that similar performance, as measured by time to complete specified route, was achieved by drivers using either the paper map or the electronic display. However, this study did show that driver visual scanning behavior was adversely affected by the moving-map system. The authors state that the novelty of the display had the effect of pulling spare driver resources toward the display.

Dingus & Hulse (1993), in reviewing this study, caution that the changes observed in scanning behavior may also reflect the distracting influence of the moving-map in the drivers' peripheral vision. These authors also discuss the results obtained by Wierwille, et al. (1991), and indicate that while in-vehicle displays may change scan patterns, drivers adapt conservative strategies when required by the environment. Therefore, while some degree of distraction may occur, drivers appear to be able to ignore the display when necessary.

Shekhar, Coyle, Shargal, Kozak, & Hancock (1991) compared response times of drivers making simple routing decisions using a head-up map. The map was presented in a north-up orientation, but the symbols depicting the driver's starting point, blocked road sections, and final destination were systematically varied. During the driving sequence, the icon representing the vehicle moved in response to driver inputs (e.g. turning steering wheel, depressing accelerator and/or brakes), while the map remained fixed. Results showed that a 1:1 mapping supported the best performance--that is, when the display was ego-centered (North & South on map = North & South in visual scene), drivers' responses were error free and quicker relative to other orientations.

While the data concerning automotive applications of rotating vs. fixed map displays is admittedly sparse, coupling these results with those presented in the aviation literature indicate that heading-up maps will facilitate superior taxiing performance. Fewer navigational errors, better tracking performance, and improved taxiing times should be expected when using a rotating map, since the momentary view of the route guidance display and FFOV will match. For this reason, it was decided to design the 2D display in our study as a rotating map. Thus, as the pilots traveled along the taxiway, the displayed information represented the taxiway environment based on the pilots' current heading.

•Dimensionality

Aviation literature

The issue of frame of reference becomes much more complex when moving from the realm of 2-D maps to that of 3-D maps. Wickens & Preveit (1995) summarized the results of studies that carefully controlled each representation to allow for accurate comparison (e.g. Andre, Wickens, Moorman, & Boschelli, 1991; Haskell & Wickens, 1993; Rate & Wickens, 1993; Wickens, et al., 1994a) and noted that, as usual, tradeoffs are present for each frame of reference. Only those issues relevant to the taxiing task will be discussed here. The authors suggest that 3-D displays can be very effective for local guidance, if they represent the world within a fully egocentric RF (e.g. viewpoint from the cockpit).

Pitted against this effectiveness are an array of costs: 1) 3-D displays introduce a degree of ambiguity regarding the precise location of points along the line of sight (see Wickens, Todd, & Seidler, 1989 for discussion of use of depth cues to reduce this ambiguity); 2) 3-D displays will present true distances at various (and therefore inconsistent) levels of resolution; and 3) a fully egocentric 3-D display will support only limited global awareness due to its limited field of view.

In examining these tradeoffs, Wickens & Preveit (1995) compared "compromise 3-D displays" (e.g. varying degrees of egocentricity) to a planar display. Their results show that precise global awareness is achieved most accurately from a 3-D "mid-exocentric" display while, as predicted, local guidance is best supported by a fully ego-referenced (e.g. more ecological) display.

Wickens (1995) summarizes some of the relevant research, and states that, contrary to some earlier comments regarding the effectiveness of 3-D displays, 2-D electronic maps will provide better lateral situation awareness compared to 3-D maps. He bases this conclusion on the assumption that the costs associated with 3-D displays will dominate the advantages discussed earlier. These costs include: 1) 2-D

maps allow for a broader viewpoint (encompasses the area behind the aircraft) without distortion; and 2) the vertical component of the elevation angle used with 3-D displays leads to a lack of resolution and thus, potential problems in estimating the location and distance of objects in the line of sight.

These factors make it difficult to predict whether 2-D or 3-D displays will best support the taxiing task. Adding to the uncertainty, it should again be noted that taxiing is a 2-dimensional task. The studies reviewed in this section examined the performance of subjects maneuvering and operating in 3 dimensions where information regarding the vertical axis was crucial. This vertical dimension is not pertinent for our present setting and may tip the balance in favor of 2D displays.

Automotive literature:

Comparatively little work has been completed comparing 2-D vs. 3-D displays for automotive applications. It was found that most studies examined the effects of using electronic vs. paper maps. In fact, in reviewing the literature, only two studies were uncovered that explicitly compared display dimensionality.

Spoerri (1993) set out to determine what type of visual display would best enable drivers to correctly maneuver through a rapid succession of intersections. He asserts that a display needs to present more information than simply what to do next; that is, giving routing instructions one intersection at a time is insufficient. In his view, operators need to be able to answer questions like: Can I keep going straight for a while after the turn? Do I need to prepare for another turn soon? Such a display would obviously support local guidance, but might also offer some awareness of the global environment. Spoerri states that the display should provide a preview of upcoming maneuvers, but wonders if such a display necessarily needs to be as complex as a detailed map commonly used.

Spoerri (1993) set out to examine these issues by comparing performance on a low-fidelity driving simulation, where subjects maneuvered along a specified route supported by either a 2-D map or a perspective guidance display. The map display consisted of a grid layout, and its current heading was always upwards. The route to follow, using appropriate directional arrows, was shown in a global coordinate system on the map display. The perspective guidance display, however, was oriented from the driver's viewpoint (e.g. ego-centered), with the sequence of route segments presented in a perspective to correspond with the order in which the driver would encounter these intersections. The subject's task was to remember the maneuvers to perform for a succession of four intersections. Results showed that the ego-centered display supported superior performance.

Spoerri (1993) then enhanced the map display to provide routing instructions in an ego-centered framework (via color-coding). The results from this manipulation indicated that there was no significant difference between the two displays. These results strongly confirm the necessity to present local guidance information in an ego-centered perspective. The author went on to propose an intermediate display which combines features from both the 2-D and 3-D displays, by keeping the current street segment oriented with the driver's viewpoint and incorporating symbols reflecting subsequent maneuvers in a global context. Spoerri suggests that such a display could minimize the amount of information processing (since the need for cognitive transformations is reduced) required of the operator and still support global awareness.

A study by Green and Williams (1992), reviewed earlier in the context of display location, is pertinent to the issue of dimensionality as well. The navigation displays used in their experiment consisted of a 2-D planar, 3-D perspective (e.g. as seen from the driver's viewpoint), and 3-D aerial (e.g. view from a low-flying aircraft) viewpoint. Subjects compared these displays to images of street

intersections photographed from a driver's perspective, and indicated if the two slides were identical. Table 2 shows the results as reported by the authors. Based on these results, Green & Williams assert that the aerial view is slightly superior to the

<u>Display view</u>	<u>Error rate</u>	<u>Mean Response Time</u>
Aerial	3.4%	1501 msec
Planar	4.5%	1523 msec
Perspective	9.9%	1706 msec

Table 2: Results for Display Perspective (Green & Williams, 1992)

planar view, and significantly better than the perspective view. Unfortunately, the results from the individual statistical analyses are not included, so definite conclusions cannot be drawn from the data. It does appear, however, that at the very least, the perspective display resulted in slower, less accurate performance. The authors believe "drivers did not respond well (objectively or subjectively) to the perspective display because many key details (e.g. cross streets) were thinner and more difficult to see". They conclude that an automotive navigation display should be an aerial view, or if technically difficult to construct such imagery, a planar view, since the differences are slight. The same limitations of this study discussed under display location are applicable here--the study employed static images and imposed only slight task demands on the subjects. While these results have intuitive value, they should be tested under more realistic conditions.

A study from research in maritime operations helps clarify the effects of display perspective on local guidance tasks in a two-dimensional environment. Schuffel (1980) compared navigator performance in a high-fidelity simulator supported by one of three display conditions: radar (2-D), outside view (3D egocentric display) & radar, outside view. The subjects piloted a 40,000 ton container vessel through a series of dike openings. Results showed the most accurate performance in the combined view (e.g. outside view & radar), while subjects using radar showed the least accurate performance. The author states that this effect is apparently caused by insufficient presentation of speed and acceleration cues on the radar display. The outside view provided preview of the upcoming maneuvers, and thus allowed the subjects to anticipate the required inputs. Schuffel assumes that the radar supports better estimation of the ship's position, and the outside view allows for the estimation of rate. This study confirms the suggestion put forward by Spoerri (1993)--combining features of both dimensions allows for better control. Ego-centered guidance information can be accompanied by preview of upcoming maneuvers, perhaps in a globally-referenced manner, to achieve efficient taxiing performance.

- Conclusions related to display perspective

Assuming that local guidance is the predominant task involved in taxiing an aircraft, the literature allows for some definite conclusions regarding an appropriate display perspective. The display should be ego-referenced, matching the momentary direction of the aircraft by rotating (e.g. track-up) in accord with pilot control inputs to the aircraft. Such a feature will reduce the cognitive demands associated with mental rotation and image comparison. There would also be a benefit of including some degree of world-referenced information for preview of upcoming maneuvers and enhanced awareness of potential hazards.

1.5 Summary & Hypotheses

Review of the pertinent literature from the fields of aviation and ground-based transportation provided some insight into the possible effects of display location and perspective on taxiing performance. However, differences between these realms make it risky to decisively state which parameter will prove superior for a route guidance display supporting taxi operations. As mentioned before, research into display design for aircraft has centered on airborne applications. Operating in two dimensions may change the interactions among the various benefits and costs seen with each parameter. While driving a vehicle may more closely approximate the task of taxiing, differences in the environmental demands and limitations imposed by the vehicle complicate the ability to generalize results. For example, the inertia of a commercial jetliner requires greater anticipation and control to maneuver around turns--the pilot may need more complex information displays than a driver.

Only recently have methods to improve navigation along the airport surface come under careful scrutiny. Jentsch (1994) investigated the effects of introducing perspective cues into the airport environment by using redesigned lighting systems. In 1991, the FAA issued new standards for airfield signs in an effort to increase the safety of ground operations (*Airman's Information Manual*, 1994). The study by Batson, et al. (1994) indicated that improvements can be realized by incorporating today's technology into the cockpit.

In an effort to extend these efforts, the present study will examine the effects of display location and perspective on taxiing performance in a high-fidelity simulator. Two display locations, head-up and head-down, will be compared while controlling for symbology format. Display symbology will be configured to evaluate some of the trends indicated by the literature, as well as reflecting some of the limitations imposed by display location. For example, projecting information head-up may induce masking or clutter. To avoid this problem as much as possible,

both the 2D and 3D displays are relatively simple in design. The perspective format can be considered partially conformal, representing the pilot's viewpoint as the aircraft moves along the taxiway. The track-up plan-view format portrays a similar region of space to the front and sides of the aircraft, and also presents routing information in an ego-centered frame. Local guidance and hazard awareness are assessed by examining the pilots' response to expected and unexpected events.

2. Experimental Design

2.1 Subjects

Thirty paid volunteers (sixteen using perspective (3D) display, sixteen using plan-view (2D) display) participated in the study. All subjects were Federal Aviation Administration (FAA) licensed pilots certified at the Private Pilot level or higher. The subjects were either students or employees recruited from flight training programs at the University of Illinois' Institute of Aviation. Subjects were randomly assigned to the groups, resulting in a balanced makeup with respect to age and total flight experience. Flight experience ranged from pilots with 100 hours and no instrument-rating to instrument-rated flight instructors with over 10,000 hours.

2.2 Scenario

Pilots were instructed to maximize speed while maintaining safe control of the aircraft as they taxied along a specified route in low visibility conditions (300' RVR = Cat IIIB conditions, which is the visibility level stated as NASA's goal for supporting taxi operations). The pilots were supported in this task by route guidance information from one of four display conditions. A 2 X 2 mixed between and within subjects design was employed to test the effectiveness of each display. Thus, a pilot in one group taxied with a 3D perspective display presented in a head-up or head-down position; while a pilot in the other group used the 2D plan-view display.

The perspective display presented a schematic 3-D outline of the taxiway out to a distance of 500 feet in front of the aircraft. This value represented a compromise between conformality of the symbology and the amount of preview provided by the display. The plan-view display was a 2-D rotating map depicting an area 500 feet in front and to the sides of the aircraft. By zooming into this level, the amount of information presented was more comparable to the perspective condition.

Also, several studies have found that a less complex map better supports route navigation (e.g. Batson, Harris, and Hunt, 1994; Popp and Farber, 1991). Finally, a more complex "zoom out" map would contain a level of clutter that could be quite disruptive in the head-up viewing condition.

The outside scene viewed by the pilots was a rendering of the Dayton International Airport environment, chosen because of its intermediate level of complexity. The simulated taxiways conformed to real-world standards for centerlines, edgeway lighting, markings, and signs. Dynamic and stationary ground traffic (e.g. aircraft) were placed along the taxi route. The pilots completed six *experimental* trials, where one trial consisted of taxiing over a 2 - 2.5 mile long route, completing several turns and a runway crossing. Both arrival and departure scenarios were used.

2.3 Apparatus

Subjects viewed a symbology set and a highly detailed outside scene depicting the surface environment of an airport as viewed from the flightdeck of a large commercial or military aircraft (e.g. simulated eye height of 20 feet above the pavement with a down angle of 10 degrees). In the head-up condition, both the symbology set and outside scene were projected onto a 6.0 meter wide by 3.0 meter high screen, which the subjects viewed from distance of 3.0 meters. In the head-down condition, the outside scene was projected onto this screen, but the symbology set was presented on a Silicon Graphics IRIS workstation with a 16 inch diagonal screen positioned 1.0 meters from the subject and approximately 25 degrees down (relative to the centerpoint of the OTW scene). When projected head-up, the display subtended an area 24° vertically and 40° horizontally, compared to an area 16.5° vertical and 25.5° horizontal when head-down. The outside scene was generated by

an Evans & Sutherland SPX500 computer, while the symbology set was generated by an IRIS Indigo computer.

The subjects controlled the simulation by manipulating a commercially obtained two-degrees of freedom joystick: acceleration resulted when the joystick was pushed forward, braking in response to pulling back, and lateral control by side motion. Rudder controls were not used. The dynamics mimicked a large aircraft in terms of inertia, speed control, and steering.

The two symbology configurations (see Figures 4 & 5) were designed using similar parameters to ensure a high degree of similarity and to avoid clutter as much as possible. All displays were color line drawings, with the taxiway pavement and all alphanumerical text represented in green, the cleared route and aircraft icons represented in white, and the stop bar symbology (when present) represented in red. Both configurations contained a conformal compass heading located near the top margin, a text display indicating present location and next turn, and an alphanumeric ground speed indicator. Other aircraft were symbolized by a chevron. Routes cleared for taxiing were displayed in each condition by highlighting the correct path. Using the perspective display (Figure 4), the pilot saw a dashed outline of the taxiway edges with a solid centerline marking the specified route. Thus, in the perspective condition, the taxiway outline and centerline symbol were partially conformal to the outside scene. A pilot taxiing with the plan-view display (Figure 5) saw a stationary aircraft symbol near the bottom of the screen depicting present location as the map moved and rotated in response to pilot inputs. The cleared route was highlighted by a dashed line. The taxiway and specified route were non-conformal in this condition. For the simulation, it was assumed that aircraft position was determined from Differential Global Positioning System (DGPS) input.

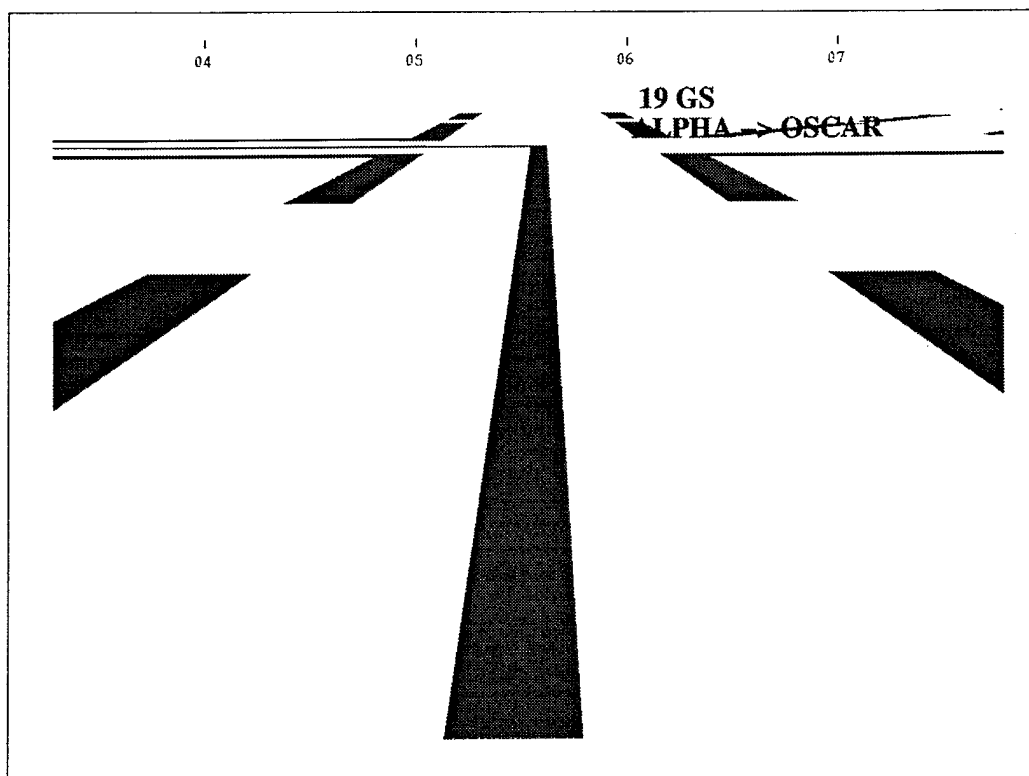


Figure 4. 3D perspective display.

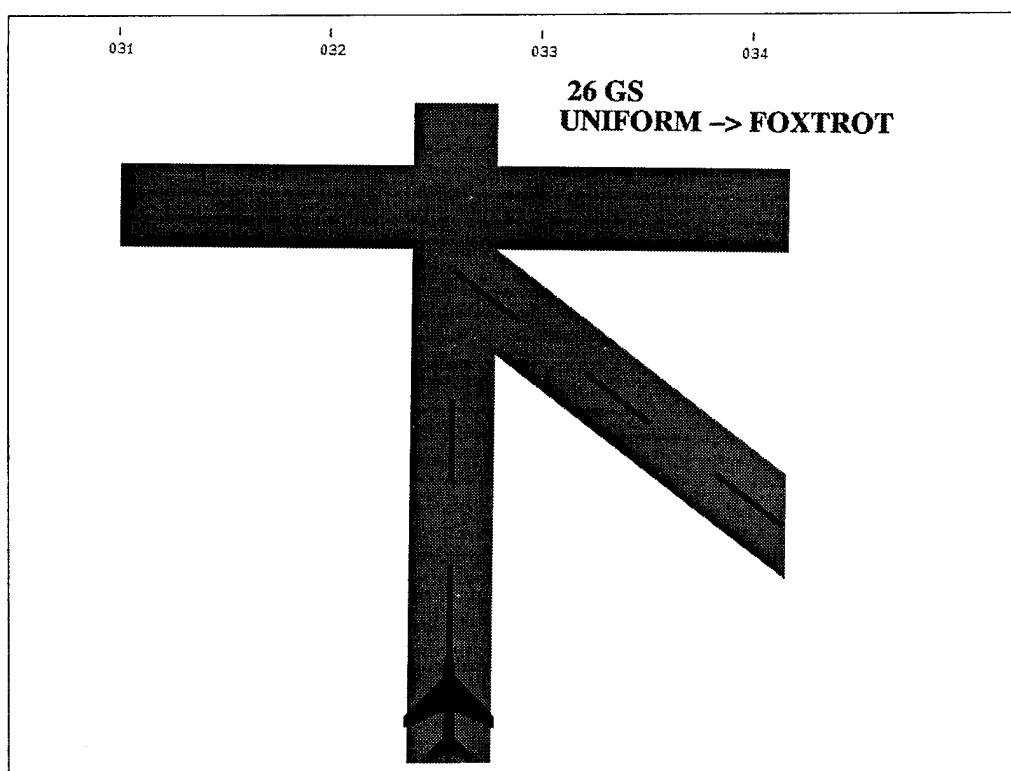


Figure 5. 2D plan-view display.

2.4 Procedure

Thirty-two pilots were randomly assigned to either the 2D or 3D display condition. Each subject completed half of the trials with the display in the head-up position, and half with the display in the head-down position. Each subject completed eight trials with the first two runs used for practice. A trial consisted of completing a specified route beginning at a runway/taxiway threshold and ending at the terminal, or starting at the terminal and ending at a specified runway. The routes were homogenous in terms of complexity, each spanning a distance of 2-2.5 miles and containing the same number of required turns (6 - 8) and runway crossings (0 - 1). The order of routes was randomized.

The trial began with the aircraft stopped at the entrance of the route. This procedure represented a compromise--it is recognized that high-speed rollofs from the runway are envisioned for the future, but in order to allow comparison of routes beginning at the terminal, each trial "started from scratch." The navigation display appeared once the subject depressed a joystick button to indicate s/he was ready to begin the trial. Routing instructions were presented on the display by means of the highlighted path and the redundant text readout indicating route clearances. Weather and lighting conditions (and thus visibility) remained constant throughout all trials (e.g. 300' RVR in daylight).

Subjects were instructed to complete the route as quickly as possible but were advised that overspeeding turns or crossing required "hold" positions would result in "penalties" (e.g. performance measures would be adjusted to reflect this behavior; see Appendix for sample instructions).

During four out of six trials, the pilot were required to respond to a query from ground control requesting an update on the aircraft's present heading, position and speed. A text box appeared near the bottom of the display requesting this information (Figure 6 & 7). The pilot responded by pressing a button on the joystick

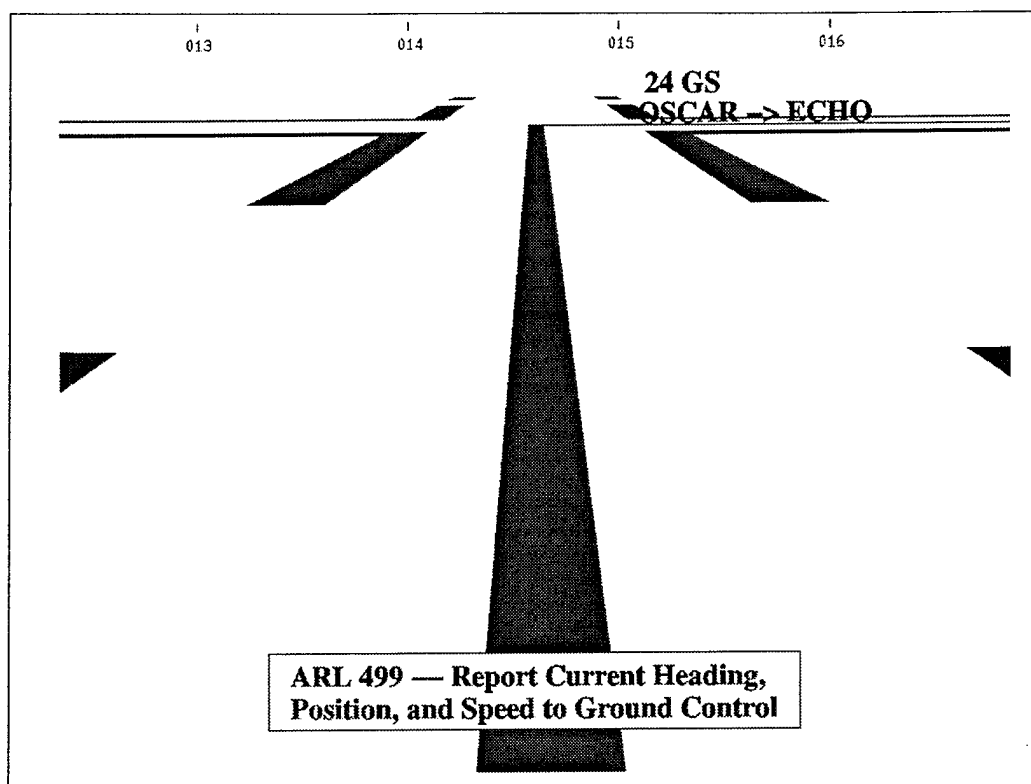


Figure 6. 3D display showing ground control query.

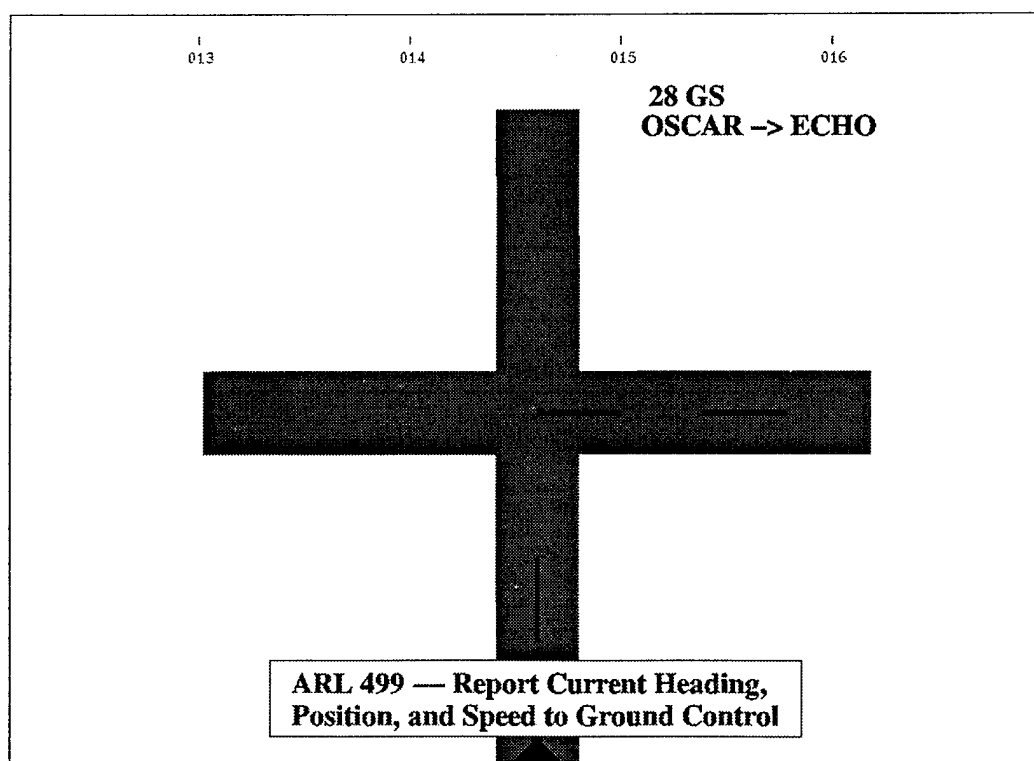


Figure 7. 2D display showing ground control query.

to initiate contact with ground control. Pilots were also informed that other ground traffic might appear along the route. Other aircraft were displayed on the navigation display (e.g. chevrons) to aid in establishing the pilot's global awareness. In four out of six trials when approaching an intersection, the pilot received instructions to "hold short" via a stop bar symbol on the display (Figures 8 & 9). Response time in initiating braking was used as the performance measure. At other times, additional aircraft were depicted on the display, but did not require the pilot to hold short. Thus, there was announced ground traffic that could either require the pilot to yield or that can be ignored. However, during two of the six trials, an unannounced object appeared in the outside scene. A small jet trainer proceeded through the intersection without yielding to the pilot. This event occurred once in the three trials for each location condition--that is, the pilot saw a moving jet once when using a head-up display, and then again while using a head-down display. The latency of initiating the braking response was used to measure this aspect of focused attention. For this measure, it was essential that subjects did not anticipate the incursion. Thus, the subjects were briefed to stop and contact ground control upon encountering any unexpected difficulties.

2.5 Performance Measures

The displays were evaluated regarding both components of successful navigation (e.g. local guidance and global awareness). The measure of average taxi speed reflects one of the primary goals of NASA's Low-Visibility Taxi Operations Group--maximizing traffic flow in adverse weather conditions. Thus, average taxi speed was calculated as an indicator of pilot strategy and performance. NASA has targeted 20 knots as the ground speed necessary to achieve optimum traffic flow. Collecting data regarding taxi speed allowed comparisons to this ideal among displays. Display effectiveness was also ascertained by recording lateral deviation

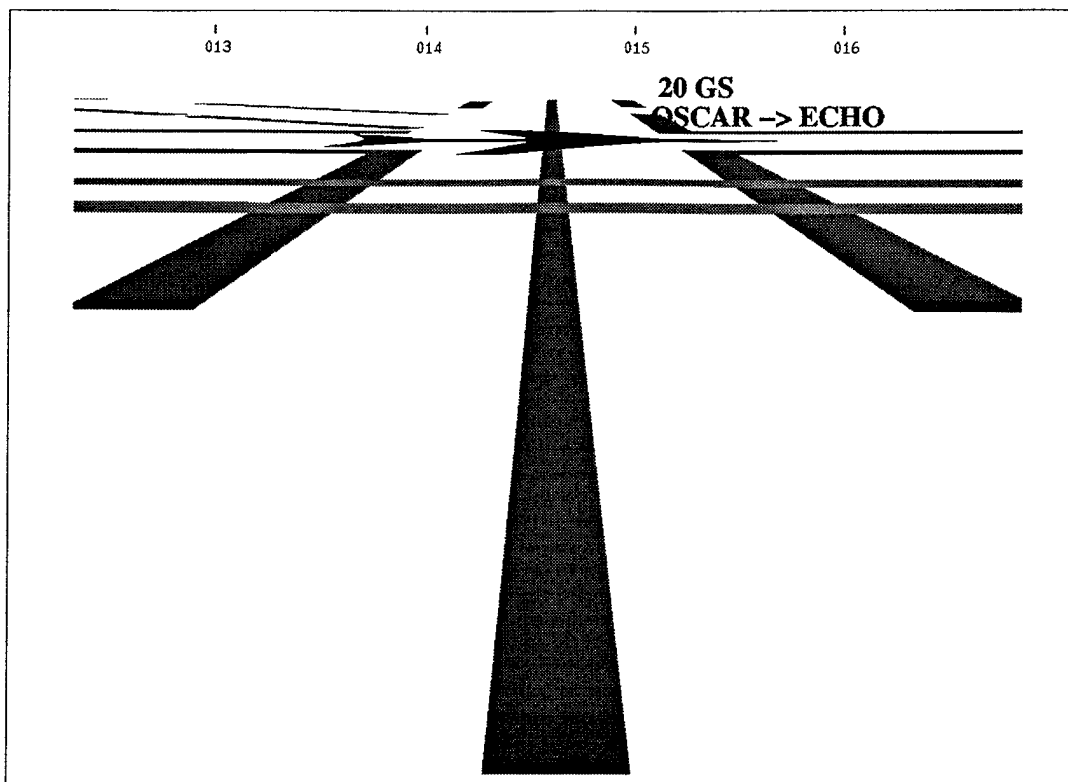


Figure 8. 3D display showing stop bar.

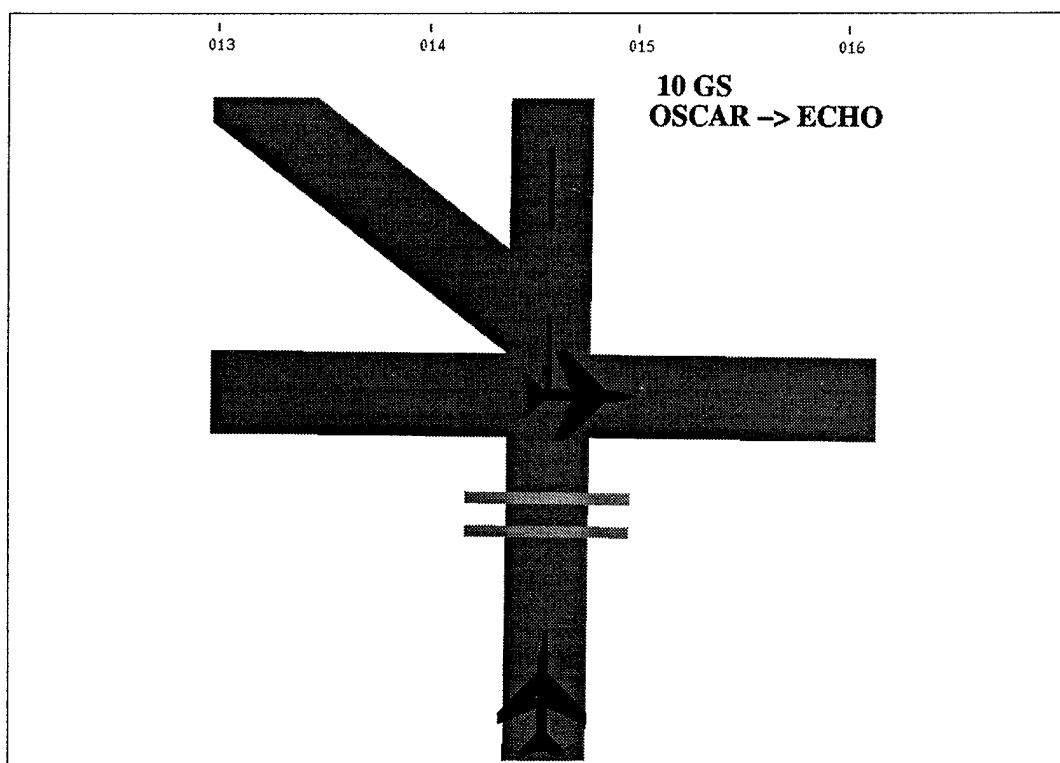


Figure 9. 2D display showing stop bar.

from the taxiway centerline (MAE) while maneuvering along straightaways in the route. Due to complexities of the simulator program, this measure was not available for tracking through the turns. Any observed instances of the aircraft's wheels rolling off the pavement was recorded in an attempt to measure pilot performance during turns. Navigational errors (e.g. wrong turns) were recorded as another indicator of a pilot's local guidance performance.

Global awareness was inferred through the measurement of response times to announced and unannounced events in both the far and near domains. Three conditions were measured: 1) Response time to reply to the query from ground control (e.g. text readout presented on display) was used to evaluate the pilots' awareness of the near domain. 2) In the announced ground traffic condition, information was available both on the display (e.g. stop bar) and in the outside scene (e.g. aircraft) which required the pilot to respond. Response time in initiating braking was used as the performance measure; 3) Finally, an unannounced event for which no alerting information was provided by the display measured the pilot's ability to detect hazards in the outside scene. As mentioned earlier, a jet trainer taxied through the intersection without stopping. Response time to initiate braking was used to infer awareness of this far domain event.

Finally, a questionnaire was administered at the end of each experiment, requesting the pilots to evaluate the display in terms of location (e.g. HUD vs. HDD), and also to comment on the unannounced events (see Appendix)--did the jet trainer surprise the pilot? How did s/he respond?

3.0 Results

3.1 Average Taxi Speed

Speed was sampled at 15 Hz and averaged for the entire trial, resulting in one data point per trial completed by each subject ($n=192$ observations). Prior to beginning formal analysis, it was noted that two potential confounds were present:

- 1) Path-one trials contained an intersection (turn 5) where the display and taxiway environment were mismatched (e.g. turn portrayed on the display did not faithfully represent the taxiway intersection). Most subjects slowed or stopped the aircraft at this intersection due to the uncertainty of which direction to proceed. In addition, eleven out of 32 subjects executed a wrong turn at this intersection, and were required to stop the aircraft, turn the aircraft around, and return to the cleared route;
- 2) Trials containing instances of a subject executing a wrong turn contained artificially lower taxi speeds. When a subject made a wrong turn, the pilot was instructed to stop, pivot the aircraft 180 degrees, and return to the correct route. This maneuvering introduced lengthy periods with a ground speed reading of zero knots, and thus lowered the average for the entire run. Based on these observations, all 32 path-one trials and 16 trials (out of 160 remaining) containing wrong turns were removed from the data.

Analysis of the remaining data at this point revealed a normal distribution with stable variances across all levels of the independent variables. The data were then averaged across display location for each subject, resulting in one data point for each display location per subject ($n=64$ means). The data were submitted to a SAS repeated measures ANOVA with display location as the repeated measure.

Analysis of the average taxi speed data revealed a significant main effect of display type $\{F(1, 30) = 4.84; p < 0.04\}$ and of display location $\{F(1, 30) = 8.67; p < 0.01\}$. There was no interaction between these variables. Viewing Figure 10, it can be seen that average taxi speed increased (by about 2 knots) when using the 2D

display, and was also increased (by about 0.5 knots) when the information, regardless of display type, was presented head-up.

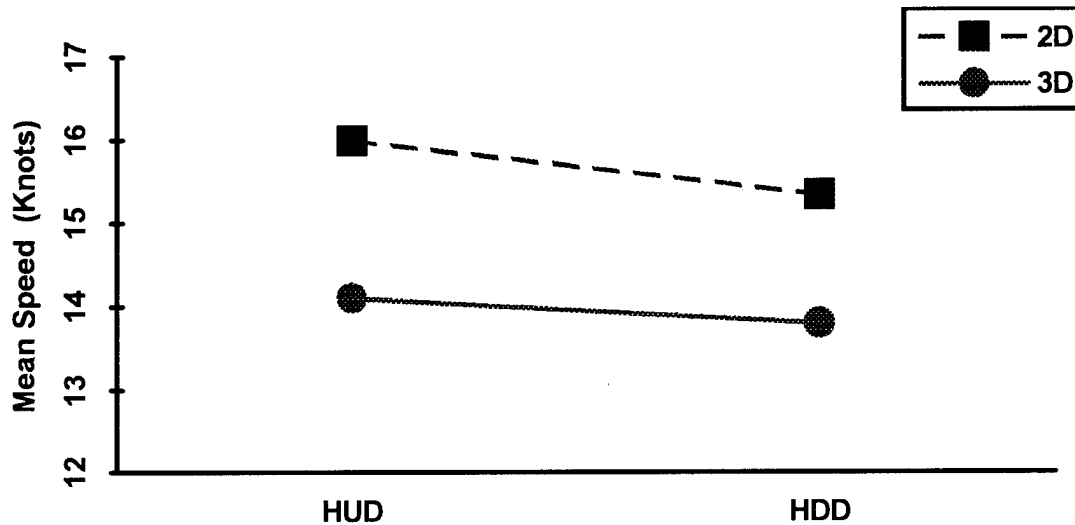


Figure 10. Mean taxi speeds for 2D and 3D display conditions.

3.2 Lateral Tracking Error

Due to programming complexities associated with the taxiway simulation and displays, lateral tracking error was measured only during straight away legs of the routes. Lateral tracking error was sampled at 15 Hz and averaged for the entire route, arriving at a single value of mean absolute error (MAE) for each trial completed by a subject ($n = 192$). It was again noted that within trials where a subject made a wrong turn, the MAE values were systematically and artificially inflated. It was assumed that in the course of maneuvering back onto the correct route, the lateral tracking error was substantially increased and resulted in overly inflated MAE values. Based on this observation, 28 trials containing wrong turns were removed from the data set (12 path-one trials plus the 16 trials noted during analysis of average taxi speed). The 16 wrong turn trials were equally distributed

across display type and location (see Table 3), so it did not appear that the two independent variables affected the proportion of “blunder” errors.

<u>Display</u>	HUD	HDD
2D	4	3
3D	5	4

Table 3. Number of wrong turns performed by subjects using each display type and location (path-one trials excluded).

The data were examined to test the statistical assumptions of normality and homoscedasticity. Two of 164 observations fell outside the specified criteria of three standard deviations from the mean, and were removed, resulting in a normally distributed sample. The data were then averaged across display location for each subject, resulting in one mean per location ($n = 64$). The data were analyzed by a SAS repeated measure ANOVA with display location as the repeated measure.

The analysis showed no significant main effects or interactions, but a marginally significant trend $\{F(1, 30) = 2.95; p = 0.096\}$ toward enhanced performance in lateral control for the 3D display was observed. Table 4 provides the respective means and standard deviations for comparison.

<u>Display type</u>	<u>n</u>	<u>MAE (feet)</u>	<u>Std Deviation</u>
2D	32	8.94	1.51
3D	32	8.31	1.19

Table 4. Mean Absolute Error (MAE) for different display types

Finally, the observed instances of an aircraft's wheels rolling off the pavement were compared, revealing no significant differences between display location or type (see Table 5). It should be noted that these errors were observed by the experimenter while the pilot maneuvered along the route. No computer algorithm was available to objectively record such deviations.

<u>Display type</u>	HUD	HDD
2D	2	3
3D	3	1

Table 5. Number of observed "wheels off pavement" errors.

3.3 Announced Ground Traffic (Near and Far Domain Event)

Subjects received instructions from ground control to hold short of an upcoming intersection by means of a stop bar presented on the display during four of the six trials (two head-up, two head-down). Response time to initiate braking immediately after the appearance of the stop bar was measured. Four subjects on four separate trials failed to respond to the stop bar, and "collided" with the aircraft taxiing through the intersection. These four data points were distributed across all display conditions (e.g. 1 subject using 2D head-up, 3 subjects using 3D head-down), indicating that no significant differences existed between groups.

Upon examining the remaining data, it became apparent that a confound existed. It had been noted that during the experiment many subjects began to decelerate upon sighting the intersection, but before the stop bar was presented. The data reflected this strategy. Unfortunately, the simulation was coded to "trigger" the stop bar event at a point 300 feet back from the intersection, well before the actual

appearance of the stop bar, but well within visual range of the intersection. As a result, the computer algorithm recorded any joystick input immediately following the trigger. Hence, recorded reaction times averaged 0.100 seconds for most trials. Given that these values are significantly quicker than values measured for simple reaction time tasks (Wickens, 1992), these data could not be used for further analysis.

3.4 Ground Control Query (Near Domain Event)

A text readout simulating a query from ground control appeared within the display in four of six trials (two head-up, two head-down). Subjects were instructed to respond by depressing a button on the joystick, simulating keying a headset microphone to initiate readback. Response time was measured as time elapsed from the onset of the text readout appearing to time to depressing the button. One subject using the 3D display failed to detect the query during the head-down condition. This data point was subsequently removed before analysis. Several subjects mistakenly responded to the text readout verbally without depressing the button (21 of 128 trials). These data points were also removed, reducing the total sample size to 106.

These data were found to be normally distributed, and were then averaged across display location for each subject, resulting in one mean per location per subject ($n = 64$). These values were analyzed with a SAS repeated measures ANOVA, with display location as the repeated measure. This analysis revealed no significant main effects or interactions for any of the independent variables (all $p > .10$).

3.5 Unannounced Jet Trainer (Far Domain Event)

A small jet trainer (T-45) taxied unannounced across the path of a pilot's aircraft on two out of six trials (one head-up, one head-down)--that is, the T-45 was

visible in the OTW scene but no display symbology indicated its presence to the pilot. Six subjects (three 2D HUD, three 2D HDD), who failed to detect the jet trainer and “collided” with it, were removed before further analysis of response times. The significance of the missed event trials can be better understood by using basic probability theory. Given that 2D subjects experienced six collision out of a possible 32 trials, the proportion of “hits” is 0.1875. On the other hand, there were no collisions during the 32 3D trials. These two proportions can be compared through the use of a “z” statistic:

$$z = (p_1 - p_2) / S_p \quad \text{where } S_p = \sqrt{p'(1 - p')(1/n_1 + 1/n_2)}$$

$$p' = (x_1 + x_2) / (n_1 + n_2)$$

and x_1, x_2 = no. of collisions; n_1, n_2 = no. of trials

$$p_i = x_i / n_i \quad (\text{where } i = 1 \text{ for 2D, } 2 \text{ for 3D})$$

Thus, for our present situation:

$$z = (0.1875 - 0) / 0.0053 \Rightarrow z = 2.5731$$

This value is used to test our hypothesis that $p_1 = p_2$ by comparing it to the two-tailed value of $z = 1.96$ ($\alpha = 0.05$). Obviously, $2.5731 > 1.96$ indicating that the 2D subjects experienced a significantly greater proportion of collisions compared to the subjects using the 3D display.

In examining the remaining data with regards to response times, it again became apparent that a confound existed. As noted for the data collected for response time to the stop bar event, many subjects began to decelerate upon sighting the intersection, but before the jet trainer appeared. The simulation was coded in a similar fashion to start the T-45 moving toward the intersection well before the jet trainer appeared in the taxiway environment, and as a result, the computer algorithm recorded joystick inputs immediately following the trigger. Hence, recorded

reaction times again averaged 0.100 seconds for most trials. Based on the reasoning presented earlier, these data also could not be used for further analysis.

3.6 Subjective Evaluation of Displays

The pilots completed a post-experiment questionnaire following completion of the last trial. An analysis of the responses revealed that pilots preferred the head-up location regardless of which display type (e.g. 2D, 3D) they used. 23 out of 32 pilots surveyed indicated that they perceived the HUD to better support taxiing performance. Examining this trend within each display type shows that, of the pilots in the 2D condition, 12 preferred the HUD, 3 favored the HDD, and one indicated no preference. Within the 3D condition, 11 pilots preferred the HUD while 2 preferred the HDD, and 3 indicated no preference for either location.

Most pilots indicated that the HUD provided them with an increased awareness of the OTW scene, and were better able to anticipate hazards and upcoming intersections.

4.0 Discussion

The objective of this study was to examine whether taxiway navigation is best supported by head-up or head-down presentation of either perspective (3D conformal) or plan-view (2D non-conformal) route guidance information. The influence of display location and egocentricity on taxi performance was assessed by measuring average speed along a designated course, lateral tracking error, and navigational errors. Coupled with these measures, the effects of the independent variables on focused and divided attention to near and far domain events were examined by presenting various combinations of information on the display and/or in the OTW scene. A pilot's ability to focus attention on the near domain display was measured by the text readout presented within the display. The ability to focus attention on the far domain was assessed by a pilot's response to an unannounced jet trainer taxiing directly across the pilot's path. Divided attention between domains (or rapid switching between domains) was assumed to be involved whenever there was relevant information for a single task contained in both domains. This situation was present for lateral guidance, speed control, and response to the announced ground traffic (e.g. stop bar).

The results of this experiment can be examined using the general framework introduced in Figure 2 and 3, as well as the literature reviewed earlier. We shall discuss the predictions made by each framework as they relate to each of the independent variables, starting with the effects of display location on the performance measures, and continuing with the effects of egocentricity on the same measures.

4.1 Location

With regards to display location, space-based theories of attention predict that presenting information head-up will create two opposing effects. On the one

hand, superimposition will create clutter and possibly degrade focused attention, leading to increased reaction times and/or reduced ability to detect events occurring in the OTW scene. On the other hand, the reduced scanning afforded by the head-up presentation may outweigh the costs of clutter. There is evidence that HUDs result in quicker detection of expected events, both on the display (near domain) and in the OTW scene (Larish & Wickens, 1991; Martin-Emerson & Wickens, 1993; Sojourner & Antin, 1990; Wickens, et al., 1993). However, when far domain events are unexpected, there appears to be a distinct disadvantage in using HUDs (Fisher, et al., 1980; Larish & Wickens, 1991; Wickens & Long, 1995).

Object-based theories of attention predict that head-up presentation would create a specific benefit for conformal symbology, allowing images to fuse into one object (Long & Wickens, 1994). Divided attention would be enhanced by such a phenomenon.

The proposed benefits of reduced scanning when presenting information head-up may help explain one significant effect related to display location. Average taxi speed was increased for both 2D and 3D displays when information was presented in the head-up location. It appears that superimposing the route guidance information on the OTW scene allowed the pilots' attention to remain "head-up". That is, with the information placed within the FFOV, the pilots' foveal and peripheral vision remained within the envelope of the external environment. Keeping "eyes out" presumably allowed pilots to maintain a faster ground speed while still being confident that they could detect and respond to events in the outside world. The responses on the post-experiment questionnaire tend to support this idea. Nearly three-fourths of the pilots indicated a preference for the HUD, with many commenting on the ability to keep their eyes focused on the taxiway when using this display location. It is also possible that the head-up location allowed for easier monitoring of the ground speed indicator located on the display. Regardless of the

cause, these results replicate findings from automotive studies (Kaptein, 1994; Sojourner & Antin, 1990) and aviation research (Long & Wickens, 1994).

The results did not reveal any benefit of display location for lateral error, suggesting that in both locations, subjects were using the same source for lateral guidance (e.g. instruments or far domain, but we are unable to discern which one). A differential benefit was not revealed for head-up presentation of conformal 3D symbology (relative to 2D) with regards to average taxi speed or lateral tracking error. Long & Wickens (1994) noted that while there was an overall advantage for HUDs in tracking performance, this advantage was enhanced for conformal symbology. The current results found no significant interaction between display type (e.g. 3D conformal) and location for any of the dependent variables.

Mean response times to the text readout also showed no significant differences between display locations. This finding sheds some light on the attentional strategies employed by the pilots in navigating the taxiway. If pilots had been primarily focusing attention on the far domain, we would expect a cost in the ability to detect this near domain event when the information was presented head-down. Given that no cost was incurred suggests that the display may have been receiving a fair and equal amount of visual attention in all conditions.

4.2 Egocentricity (2D vs. 3D)

We initially proposed that the 3D conformal symbology would better support taxiway navigation based on studies indicating that local guidance information should be presented from a fully egocentric perspective (Haskell & Wickens, 1993; Spoerri, 1993; Wickens & Prevett, 1995). The findings from this study are partially consistent with this assertion.

It is important to note, that the conclusion that "local guidance is better supported by ego-referenced information" is based upon evaluation of lateral and

vertical tracking error (Haskell & Wickens, 1993; Wickens & Prevett, 1995). In fact, Haskell & Wickens (1993) found that 2D (exocentric) displays actually supported better longitudinal control. The present study replicated this finding, noting that average taxi speed showed an advantage of almost two knots for the 2D display. This finding is very likely related to the costs associated with displaying information in a 3D format. As discussed in the Introduction, 3D displays introduce ambiguity regarding the precise location of points along the line of sight, produce inconsistent levels of resolution, and most importantly for the present discussion, present a limited FOV. This last factor provides one important explanation for the slower taxi speeds associated with the 3D display.

Viewing Figure 6, it can be seen that the 2D display represented a larger region of space surrounding the aircraft. This increased FOV provided the pilots with lateral preview, which allowed pilots to better anticipate upcoming maneuvers and begin to plan control inputs. Thus, pilots could enhance their speed throughout the route.

Related to this lateral preview, the 2D display also represented the approaching intersection in such a way as to create a “temporal preview”--that is, the map provided a linear representation of the distance (and thus time) to the intersection. The pilots could use the display to optimize their control inputs, resulting in increased speeds.

Pilots supported by the 3D display received information from a narrower FOV (see Figure 5). The approaching intersections were more difficult to detect at a similar distance. The pilots may have elected to adopt a slower speed through the entire route to maximize their ability to monitor for upcoming turns and/or potential hazards. With regards to the “temporal preview” afforded by the 2D display, the 3D display represented the taxiway environment from the pilot’s perspective. Thus, an approaching intersection would remain stationary when first appearing on the

display, but later loom toward the pilot as the distance to the intersection decreased. This phenomenon prevented the 3D display from providing a “countdown” to the next turn, and again, may have caused the pilots to adopt a more conservative (e.g. slower) speed.

Another possible explanation for the increased mean taxi speeds under the 2D condition is based upon differences in the processing of motion cues and visual flow. The aircraft icon centered on the bottom of the 2D display appeared to move more slowly relative to the taxiway symbology. If a pilot based his control inputs on this display feature, s/he may have been inclined to increase the aircraft’s taxiing speed. Wickens (1992) discusses the potential bias in human perception that occurs because our subjective perception of speed is heavily influenced by global optical flow. This explanation would be consistent with the incidents reported when the Boeing 747 was first introduced. Pilots taxied the aircraft at speeds exceeding the design limits and occasionally damaged the undercarriage while maneuvering around turns. These pilots were accustomed to taxiing the previous generation of narrow-bodied aircraft that were much lower to the ground relative to the 747. As a result, the pilots seated in the cockpit of the 747 perceived their speed as being slower. Conversely, the 3D display contained dashed lines outlining the taxiway pavement which created an impression of greater speed. These cues of global optical flow were more salient compared to the 2D display, and may have prompted the pilots in the 3D condition to pull back on the throttle.

There was a trend toward a 3D advantage in minimizing lateral error which again replicated earlier findings (Haskell & Wickens, 1993). While of only marginal statistical significance, the values for MAE indicate that pilots using the 3D display achieved slightly better lateral control throughout the trials. Three explanations may contribute to this trend. First, as noted above, 3D subjects taxied at a slower average speed. By traveling more slowly, the pilot could achieve better lateral control (e.g.

speed-accuracy tradeoff). Second, although these displays were not designed as a tracking display, the symbology representing the cleared route on the 3D display was significantly wider and more salient compared to the corresponding symbology presented on the 2D display. This physical increase in the resolution of the error scale may have allowed for more precise tracking in the 3D condition. Finally, it is simply possible that the more "ego-referenced" display provided a more natural, intuitive, and therefore effective, means of lateral control.

With regard to the unannounced T-45 event, it was mentioned earlier that, of the six collisions that occurred, all involved subjects using the 2D display. As the earlier analysis showed, this difference is significant, but it remains difficult to speculate on the cause behind this trend. It could be argued that the 2D display demands greater information processing resources, such that when a pilot is attending to the route guidance information, s/he is less able to divided attention to the external environment and thus fails to detect a potential hazard. It can also be argued that because of its partial conformality, the 3D display "blends" with its far domain counterpart to a greater degree, and thus allows for more effective integration (independent of its location). The 3D display represented the upcoming intersection from pilot's point-of-view. As Figure 3 indicates, such a display will enhance image comparison (e.g. "what you see is what you get"). Thus, when the jet trainer appeared in the OTW scene, no transformation of the display imagery was necessary and the pilots were able to detect the aircraft more easily. The 2D display, on the other hand, may have imposed greater requirements on the pilots (e.g. translation, image comparison). This processing, in turn, may have lead to the observed collisions.

One point regarding this finding needs clarification. It could be argued that pilots using the 2D display collided with the jet trainer more often simply because, on the average, they were traveling at faster speeds. If this were true, then although

the 2D pilots may detect the T-45 with equal frequency, the greater inertia of the aircraft would carry the pilot into the intersection even if braking had been initiated. This explanation, however, appears inadequate once the actual dynamics of the simulation are considered. In setting up the unannounced ground traffic event, it was decided to trigger the event in such a way that, even if traveling at the maximum allowable speed (e.g. 30 knots), the pilot would be able to detect and respond safely to the jet trainer. Even with the faster average taxi speeds observed for the 2D condition, these speeds were well within the safety envelope. Thus, the six collisions represent a dynamic of attentional processing, not a simple result of physical laws.

4.3 General Discussion and Practical Implications

In conclusion, our results have both practical applications for the Terminal Area Productivity (TAP) program and theoretical implications for developing a model of HUD processing. Wickens & Preveit (1995) noted that tradeoffs often exist between different displays. This observation holds true for our study as well. It appears that 2D display supports taxiing speeds that are 2 knots faster than the 3D display. Does this modest increase have practical benefits? When considering this increase over the long term, it could result in more efficient taxiing, reduced fuel consumption, and, hopefully, reduced surface congestion. Despite this advantage, it should also be kept in mind that pilots supported by the 2D display failed to detect unexpected ground traffic on six separate occasions. As discussed earlier, we believe that this trend reflects increased processing demands imposed by the display rather than an outcome of greater taxiing speeds. The 3D display supported slightly better lateral tracking performance with no observed shortcomings in detecting far domain events. The strengths and weaknesses of one display could potentially

compliment the strengths and weaknesses of the other display if both displays are used.

The driving forces of optimizing surface traffic flow (e.g. reduced runway occupancy time, greater average taxi speeds) and improved situation awareness could be addressed by placing both displays into the multi-crew cockpit. A 2D map display could present a wider FOV for better anticipation of upcoming maneuvers and hazards, resulting in higher taxi speeds. The information on this display could be read by one pilot while the other controls the aircraft. The pilot in control of the aircraft could benefit from using a 3D display (either head-up or head-down)--lateral tracking could be improved, while far domain events (e.g. ground traffic) may be more readily detected. This concept should be tested further by employing a multi-crew design in a high-fidelity simulator.

These results have theoretical implications as well. The design of this study permitted a pilot's attentional focus to be on one of three areas: the head-up display, the head-down display, or the outside environment (far domain). The fact that response times to the ground control query were equivalent suggests that the pilots' attention was focused more often on the near domain. Moving the display information (e.g. near domain) to a head-up position allowed the pilots to achieve better far domain monitoring and maintain greater confidence in the ability to detect far domain objects, which led to greater taxi speeds. Given that the display was relatively uncluttered, the detection of far domain events was not disrupted (unlike Long & Wickens, 1994), and because symbology contrast was good, the display did not disrupt detection or processing of near domain instrumentation and events (unlike May & Wickens, 1995).

Changing the display format to 2D provided more precise speed control and braking information (e.g. lateral preview, linear information regarding distance to intersection). However, this symbology can not be "fused" with the far domain, so

attention is drawn “inward” to the extent that it disrupts far domain detection (e.g. 6 collisions out of 32 trials). This disruption is due to the dynamics of attention, not clutter, since these collision occurred with equal frequency in both the head-up and head-down locations. These results suggest that the “tradeoff battle” between scanning and clutter tends to slightly favor reduced scanning benefits (e.g. HUD), perhaps in part because the displays were relatively uncluttered. This finding supports the suggestions espoused by many researchers (Ashby & Parkes, 1993; Schraagen, 1993; Weintraub & Ensing, 1992) that displays present only information critical to the task. Pilot performance was effectively supported by the displays despite their relative simplicity. When placed into a modern cockpit for use in a dynamic and complex environment, this display feature may become crucial.

Appendices

Appendix 1 -- Instructions for subjects using the 3D display.

!!PLEASE READ THESE INSTRUCTIONS CAREFULLY!!

(3-D)

Reason for the Study.

Ground operations at many airports are already congested and confusing. Several runway incursions and ground vehicle mishaps have received recent publicity. The problem may get worse. With improvements in technology, both NASA and the FAA are moving to increase the efficiency of airborne traffic. Without similar improvements in surface operations, particularly in low-visibility conditions, the bottleneck of ground ops will narrow even further, increasing the risks and confusion. NASA is currently investigating methods to enhance ground traffic movement. The purpose of this NASA-sponsored study is to compare different types of route guidance displays to determine what features can best support taxiway navigation. This study is the first step towards designing displays that improve pilot situation awareness and performance in taxi operations.

Background.

You will be trying to maneuver a large aircraft along the taxiway, proceeding as expeditiously as possible while supported by an electronic route guidance display presented either head-up or head-down. Visibility is 300 feet RVR under daylight conditions. Routing instructions will be provided by datalink (electronic readout), and presented on the route guidance display. A total of eight runs will be completed. The first two runs will be used to familiarize yourself with the system and display, while the other runs will be recorded. The airport layout is based on the Dayton International Airport.

The Display.

The route guidance display you will be using is a *perspective display* that presents a schematic 3-D outline of the taxiway out to a distance of 500 feet in front of your aircraft. On half of the taxi runs, the display will be projected head-up on the outside scene, while on the other half, it will be presented head-down on a computer screen directly in front of you. The display presents several important elements (see Figure 1):

- Taxiway pavement is outlined as green dashed-lines, and will align to the real-world taxiway as you taxi along. That is, the display shows the taxiway from your viewpoint. The display will give you some preview of upcoming segments (e.g. 500 feet in front of aircraft).

- The cleared route to be followed is a solid line in the center of the outlined taxiway edges (e.g. "follow the solid line road").

Appendix 1 (continued)

-Routing directions will also be presented in the upper right corner of the display. The display will present your present location and the next taxiway to follow. For example, if you were on taxiway Charlie, and were cleared to turn on taxiway Oscar, the display would show: CHARLIE -> OSCAR.

-Do not become too engrossed in using the display. Due to differences in the programming codes, the taxiway symbology on the display does not exactly overlay the real-world pavement. In other words, monitor the outside scene to stay as close as possible to the yellow taxiway centerline, and keep your wheels on the pavement.

-Ground speed will be displayed in "knots", and is also located in the upper right corner of the display.

-Heading information will be presented as a conformal heading scale at the top of the display. The scale is set at 10 degree increments, with the cardinal directions (North, South, East, West) marked as N, S, E, W.

-Periodically throughout the runs, you will receive updated instructions or queries from ground control. These may appear on the display as 1) a "HOLD SHORT" bar (see Figure 2) indicating that another aircraft is proceeding through the intersection. Once the aircraft is clear of the intersection, depress the red joystick button to proceed; 2) as a text readout near the bottom of the display (see Figure 3). Depress the red joystick button as quickly as possible to respond, and follow the instructions.

-The simulated airport environment reflects real-world conditions as closely as possible. Maintain awareness of possible hazards, your geographical location, and changes in routing clearances throughout the entire route. If you become disoriented, lost, or encounter any difficulties, stop immediately and contact ground control by keying the red button on top of the joystick. Verbally report the situation and/or any requested information. Wait for additional instructions from ground control.

Your Task.

All taxi runs begin with your aircraft parked at the entrance of the route. Press the red joystick button to make the display appear and begin the run. Follow the highlighted route presented on the display. Routing directions are also available in the upper right corner of the display. Unless otherwise directed, you are cleared to taxi across all runways. Complete the route as quickly as possible, but do not overspeed turns or cross designated "hold positions". Maximum speed on straightaways is 30 kts. Monitor the outside scene and maintain awareness of the display to optimize performance. Remember, you are a professional, responsible for the safety and well-being of your crew, passengers and cargo.

Appendix 1 (continued)

Performance Measures.

Your performance in taxiing with the route guidance display will be measured in several ways. The computer will record the total time it took to complete the course, your speed, and lateral deviation from the taxiway centerline, since NASA's goal is to safely maximize ground traffic flow. Time to respond to ground control directives (e.g. stop bar) or requests will be recorded. Navigational errors (e.g. wrong turns) will be recorded by the observer. All of these measures will be used to determine how well this display supported your taxiing performance.

THANKS FOR TAKING TIME TO PARTICIPATE.

Appendix 2 -- Instructions for subjects using 2D display.

!!PLEASE READ THESE INSTRUCTIONS CAREFULLY!!

(2D Map)

Reason for the Study.

Ground operations at many airports are already congested and confusing. Several runway incursions and ground vehicle mishaps have received recent publicity. The problem may get worse. With improvements in technology, both NASA and the FAA are moving to increase the efficiency of airborne traffic. Without similar improvements in surface operations, particularly in low-visibility conditions, the bottleneck of ground ops will narrow even further, increasing the risks and confusion. NASA is currently investigating methods to enhance ground traffic movement. The purpose of this NASA-sponsored study is to compare different types of route guidance displays to determine what features can best support taxiway navigation. This study is the first step towards designing displays that improve pilot situation awareness and performance in taxi operations.

Background.

You will be trying to maneuver a large aircraft along the taxiway, proceeding as expeditiously as possible while supported by an electronic route guidance display presented either head-up or head-down. Visibility is 300 feet RVR under daylight conditions. Routing instructions will be provided by datalink (electronic readout), and presented on the route guidance display. A total of eight runs will be completed. The first two runs will be used to familiarize yourself with the system and display, while the other runs will be recorded. The airport layout is based on the Dayton International Airport.

The Display.

The route guidance display you will be using is a rotating 2-D map "zoomed in" to depict the area 500 feet in front and to the sides of your aircraft. On some of the taxi runs, the display will be projected head-up on the outside scene, while on others it will be presented head-down on a computer screen directly in front of you. The display presents several important elements (see Figure 1):

- Pavement is presented as solid green, and will align to the real-world taxiway as you move along. That is, the display will rotate to match your viewpoint outside the aircraft. The display will give you some preview of upcoming segments (e.g. 500 feet in front and to the sides).

- The cleared routes to be followed are white dashed-lines in the center of the green taxiway (e.g. "follow the white dashed-line road").

- Routing directions will also be presented in the upper right corner of the display. The display will present your present location and the next taxiway to

Appendix 2 (continued)

follow. For example, if you were on taxiway Charlie, and were cleared to turn on taxiway Oscar, the display would show: CHARLIE -> OSCAR.

- Do not become too engrossed in using the display. In other words, monitor the outside scene to stay as close as possible to the taxiway centerline, and keep your wheels on the pavement.

- Ground speed will be displayed in "knots", and is also located in the upper right corner of the display.

- Heading information will be presented as a heading scale at the top of the display. The scale is set at 10 degree increments, with the cardinal directions (North, South, East, West) marked as N, S, E, W.

- Periodically throughout the runs, you will receive updated instructions or queries from ground control. These may appear on the display as 1) a "HOLD SHORT" bar (see Figure 2) indicating that another aircraft is proceeding through the intersection. Once the aircraft is clear of the intersection, depress the red joystick button to proceed; 2) as a text readout near the bottom of the display (see Figure 3). Depress the red joystick button as quickly as possible to respond, and follow the instructions.

- The simulated airport environment reflects real-world conditions as closely as possible. Maintain awareness of possible hazards, your geographical location, and changes in routing clearances throughout the entire route. If you become disoriented, lost, or encounter any difficulties, stop immediately and contact ground control by keying the red button on top of the joystick. Verbally report the situation and/or any requested information. Wait for additional instructions from ground control.

Your Task.

All taxi runs begin with your aircraft parked at the entrance of the route. Press the red joystick button to make the display appear and begin the run. Follow the highlighted route presented on the display. Routing directions are also available in the upper right corner of the display. Unless otherwise directed, you are cleared to taxi across all runways. Complete the route as quickly as possible, but do not overspeed turns or cross designated "hold positions". Maximum speed on straightaways is 30 kts. Monitor the outside scene and maintain awareness of the display to optimize performance. Remember, you are a professional, responsible for the safety and well-being of your crew, passengers and cargo.

Performance Measures.

Your performance in taxiing with the route guidance display will be measured in several ways. The computer will record the total time it took to

Appendix 2 (continued)

complete the course, your speed, and lateral deviation from the taxiway centerline, since NASA's goal is to maximize ground traffic flow. Time to respond to ground control directives (e.g. stop

bar) or requests will be recorded. Navigational errors (e.g. wrong turns) will be recorded by the observer. All of these measures will be used to determine how well this display supported your taxiing performance.

THANKS FOR TAKING TIME TO PARTICIPATE.

Appendix 3 -- Post-experiment questionnaire used to survey pilot preferences, etc.

Post-Experiment Questionnaire

Name: _____

1. Which display location did you prefer? (circle one)

Head-up

Head-down

No preference

2. Were you surprised by the first taxiway incursion (e.g. red & white T-45 jet trainer)?

Y N

3. Did you initiate braking as soon as you saw the jet trainer taxiing through the intersection? Y N

4. Were you surprised by the second incursion (e.g. red & white T-45 jet trainer)?

Y N

5. Did you initiate braking as soon as you saw the jet trainer taxiing through the intersection? Y N

Please add any comments regarding the format of the route guidance display which you feel helped and/or hurt your performance:

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